University of Alberta

Integrated Control of Canada Thistle in Pasture and Its Effects on Forage Production

by

Chad William Grekul

A thesis submitted to the faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

In

Rangeland and Wildlife Resources

Department of Agriculture, Food and Nutritional Science

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Integrated Control of Canada Thistle in Pasture and Its Effects on Forage Production** submitted by Chad William Grekul in partial fulfillment of the requirements for the degree of Master of Science in Rangeland and Wildlife Resources.

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ABSTRACT

Several field experiments were conducted from 1999 to 2002 to assess forage yield reductions caused by Canada thistle, and to investigate integrated approaches to controlling thistle in central Alberta pastures.

Canada thistle reduced forage biomass at more than one location, but this response varied among pastures. Site differences such as initial thistle density and biomass, local growing conditions and moisture regime, rodent disturbances, and soil type or nutrient status, likely contributed to the varied responses among sites.

Fertilization enhanced thistle control with herbicides for two years after spraying, likely due to increased competition from the grass stand. One-time mowing did not provide adequate control of thistle, and when combined with fertilization, increased thistle abundance.

Sponge-wiper applied glyphosate reduced Canada thistle, but also decreased grass production and increased annual weeds. Wiper-applied clopyralid and picloram+2,4-D provided thistle suppression for up to two years following a one-time treatment. All selective broad-leaf herbicides tested reduced legumes, but maintained grass production.

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Table of Contents

Chapter	Page
1. INTRODUCTION	1
1.1 Background	1
1.2 Research Objectives	4
1.3 Literature Cited	5
2. LITERATURE REVIEW	7
2.1 Canada Thistle [*Cirsium arvense* (L.) Scop.]	7
2.1.1 Taxonomy	7
2.1.2 Biology	8
2.1.3 Habitat and Distribution	13
2.2 Nature of the Problem	16
2.3 Control of Canada thistle	19
2.3.1 Cultivation	20
2.3.2 Biological Control	20
2.3.3 Mowing	21
2.3.4 Grazing	23
2.3.5 Herbicides	24
2.3.6 Fertilization and Competition	28
2.4 Literature Cited	32
3. PASTURE FORAGE YIELD LOSS DUE TO CANADA THISTLE	40
3.1 Introduction	40
3.2 Materials and Methods	42

3.2.1 Study Sites 42

3.2.2 Field Sampling 43

3.2.3 Analysis 46

3.3 Results and Discussion 48

3.3.1 Overall Yield Loss Trends 48

3.3.2 Site Specific Responses 50

3.3.3 Comparison of Thistle Variables 54

3.4 Conclusions and Management Recommendations 57

3.5 Literature Cited 60

4. INTEGRATED EFFECTS OF FERTILIZATION WITH HERBICIDE AND MOWING TREATMENTS ON CANADA THISTLE ABUNDANCE AND PASTURE FORAGE PRODUCTION 72

4.1 Introduction 72

4.2 Materials and Methods 75

4.2.1 Study Sites 75

4.2.2 Experimental Design 76

4.2.3 Vegetation Sampling and Forage Quality Analysis 78

4.2.4 Analysis 80

4.3 Results 81

4.3.1 Canada Thistle Control 82

4.3.2 Tall Buttercup and Perennial Sow-thistle Control 84

4.3.3 Forage Production Responses 84

4.3.4 Forage Quality Responses 85

4.3.5 Species Composition Responses 86

4.4 Discussion 86

4.5 Conclusions and Management Recommendations 95

4.6 Literature Cited 98

5. SPONGE WIPER APPLICATION OF HERBICIDES FOR CANADA THISTLE CONTROL IN PASTURES 116

5.1 Introduction 116

5.2 Materials and Methods 119

5.2.1 Study Sites 119

5.2.2 Experimental Design 120

5.2.3 Vegetation Sampling 122

5.2.3.1 Glyphosate Experiment 123

5.2.3.2 Multiple Herbicides Experiment 124

5.2.4 Analysis 125

5.2.4.1 Glyphosate Experiment 125

5.2.4.2 Multiple Herbicides Experiment 126

5.3 Results and Discussion 127

5.3.1 Effects of Wiper-Applied Glyphosate 127

5.3.1.1 Canada Thistle Control 127

5.3.1.2 Effects on Forage Production 129

5.3.2 Effects of Wiper-Applied Selective Herbicides 133

5.3.2.1 Canada Thistle Control 133

5.3.2.2 Effects on Forage Production and Sward Components 137

5.4 Conclusions and Management Recommendations 140

5.5 Literature Cited 143

6. SYNTHESIS / CONCLUSION 154

6.1 Literature Cited 159

Appendix 1: Maps of the study locations. 160

Appendix 2: Soil descriptions. 163

List of Tables

Table **Page**

Table 3.1 Physical site (i.e., soil) characteristics of the eight yield loss assessment sites, as sampled in May 1999. 63

Table 3.2 Vegetation characteristics of the eight yield loss assessment sites, as sampled in August 1999. 64

Table 3.3 Growing season (May 1-August 31) precipitation for the 8 yield loss sites for 1999, 2000, and 2001, as well as the regional 30-year averages. 65

Table 3.4 Relationships between total herbage yield ($kg \cdot ha^{-1}$) and three predictors (i.e., indicators of Canada thistle abundance) over three years at 4 sites in central Alberta. 66

Table 3.5 Relationships between grass yield ($kg \cdot ha^{-1}$) and three predictors (i.e., indicators of Canada thistle abundance) over three years at 4 sites in central Alberta. 67

Table 3.6 A comparison of the number of significant correlations between the three thistle variables and forage parameters measured in 1999, 2000, and 2001. ... 68

Table 4.1 Locations, landscape characteristics, and growing season precipitation for the four pasture research sites. 103

Table 4.2 Dominant plant species composition of the four pasture sites, as sampled in August 1999. 103

Table 4.3 Vegetation characteristics of the four pasture research sites, as sampled in August 1999. 104

Table 4.4 Soil characteristics of the four pasture research sites, as sampled in May 1999. 104

Table 4.5 Dates of mowing and herbicide application, as well as fertilizer application and vegetation sampling for the three years of the thistle control study. 105

Table 4.6 Means and pooled SEs, as well as ANOVA *F* test significance values for percent thistle control (visual estimates) and thistle shoot density by thistle control treatment, fertilization, and treatment X fertilization combinations, from 4 pasture sites in central Alberta for 1999 to 2001. 106

Table 4.7 Means and pooled SEs, as well as ANOVA *F* test significance values for thistle biomass and thistle biomass per stem by thistle control treatment, fertilization, and treatment X fertilization combinations, from 4 pasture sites in central Alberta for 1999 to 2001 107

Table 4.8 Means and pooled SEs, as well as ANOVA *F* test significance values for tall buttercup and perennial sow-thistle variables by thistle control treatment, fertilization, and treatment X fertilization combinations, from pasture Sites 3 and 4, respectively (Rocky Mountain House and Two Hills), for 1999 to 2001. 108

Table 4.9 Means and pooled SEs, as well as ANOVA *F* test significance values for grass and forb biomass by thistle control treatment, fertilization, and treatment X fertilization combinations, from 4 pasture sites in central Alberta for 1999 to 2001. 109

Table 4.10 Means and pooled SEs, as well as ANOVA *F* test significance values for grass crude protein content and yield by thistle control treatment, fertilization, and treatment X fertilization combinations, from 4 pastures sites in central Alberta for 1999 to 2001. 110

Table 4.11 Means and pooled SEs, as well as ANOVA *F* test significance values for grass phosphorus and acid detergent fiber (ADF) content by thistle control treatment, fertilization, and treatment X fertilization combinations, from 4 pastures sites in central Alberta for 1999 to 2001 111

Table 4.12 Means and pooled SEs, as well as ANOVA *F* test significance values for forb crude protein content and yield by thistle control treatment, fertilization, and treatment X fertilization combinations, from 2 pastures sites in central Alberta for 1999 and 2000 112

Table 4.13 Means and pooled SEs, as well as ANOVA *F* test significance values for forb phosphorus and acid detergent fiber (ADF) content by thistle control treatment, fertilization, and treatment X fertilization combinations, from 2 pastures sites in central Alberta for 1999 and 2000 113

Table 4.14 Means and pooled SEs, as well as ANOVA *F* test significance values for species richness and diversity by thistle control treatment, fertilization, and treatment X fertilization combinations, from 4 pastures sites in central Alberta for 1999 to 2001. 114

Table 4.15 Means and pooled SEs, as well as ANOVA *F* test significance values for native species and legume cover by thistle control treatment, fertilization, and treatment X fertilization combinations, from 3 pastures sites in central Alberta for 1999 to 2001. 115

Table 5.1 Location, soils, and vegetation characteristics for Experiment 1 (glyphosate-wiper) and Experiment 2 (multiple herbicides-wiper) pasture sites as sampled in August and September of 1999, and August of 2000, respectively. 148

Table 5.2 Soil characteristics for the three pastures sites of the multiple herbicides experiment, as sampled in August of 2001 149

Table 5.3 Precipitation data for the four sites of the glyphosate wiper experiment (1999.–2001), and the three sites of the multiple herbicides experiment (2000 – 2002). 149

Table 5.4 Means and pooled SEs, as well as ANOVA *F* test significance values for Canada thistle variables, by timing of application, wiper treatment, and timing X wiper treatment combinations from 4 pasture sites in central Alberta for 1999 to 2001 (glyphosate experiment). 150

Table 5.5 Means and pooled SEs, as well as ANOVA *F* test significance values for annual net primary production variables, by timing of application, wiper treatment, and timing X wiper treatment combinations, from 4 pasture sites in central Alberta for 1999 to 2001 (glyphosate experiment)..... 151

Table 5.6 Means and pooled SEs, as well as ANOVA *F* test significance values for Canada thistle variables, by wiper herbicide treatment, from 3 pasture sites in central Alberta for 2000 to 2002 (multiple herbicides experiment)..... 152

Table 5.7 Means and pooled SEs, as well as ANOVA *F* test significance values for annual net primary productivity variables by wiper herbicide treatment, from 3 pasture sites in central Alberta for 2001 and 2002 (multiple herbicides experiment). 153

Table 5.8 Means and pooled SEs, as well as ANOVA *F* test significance values for legume and dandelion cover by wiper herbicide treatment at two pasture sites in central Alberta for 2002..... 153

List of Figures

Figure **Page**

Figure 3.1 Relationship between grass yield ($kg \cdot ha^{-1}$) and large plot Canada thistle density ($shoots \cdot m^{-2}$) for Site 1 in 1999, 2000, and 2001. 69

Figure 3.2 Relationship between grass yield ($kg \cdot ha^{-1}$) and large plot Canada thistle density ($shoots \cdot m^{-2}$) for Site 3 in 1999 and 2000. 70

Figure 3.3 Relationship between herbage yield ($kg \cdot ha^{-1}$) and Canada thistle yield ($g/0.25\ m^2$) for Site 4 in 1999, 2000, and 2001. 71

1. INTRODUCTION

1.1 Background

Canada thistle [*Cirsium arvense* (L.) Scop.] is an aggressive, perennial weed endemic to Europe, western Asia, and northern Africa (Hayden 1934; Hodgson 1968; Donald 1990). Since its introduction to North America in the 1700's as an impurity in farm seed, Canada thistle has become widespread throughout Canada and the United States, and is now found in all provinces in Canada as far north as 59° (Detmers 1927; Hayden 1934; Hodgson 1968; Moore 1975; Donald 1990). In Alberta alone, it was reported to infest 4 million ha of cultivated land in the early 1960's, and by 1997, was found in 53% of all cereal and oilseed fields surveyed in the province (Alex 1966; Thomas et al. 1998).

While much has been researched and written about Canada thistle in annual crops, few studies have addressed this problem weed in pastures or hay land, especially in western Canada. This is despite the fact that Canada thistle has been cited as a serious concern in pastures, rangeland, and perennial forage crops in temperate regions throughout the world, including the United States and Canada (Hodgson 1968; Moore 1975; Donald 1990). The few Canadian weed surveys that have included forage crops in their sampling, generally have found that Canada thistle was a problem in pasture, hay land, and alfalfa (*Medicago sativa* L.) seed fields (Thomas and Wise 1983; Goodwin et al. 1986; Moyer et al. 1991).

The weedy character of Canada thistle is attributed mostly to its extensive, creeping root system, which can survive adverse conditions and regenerate from fragments as small as 8 mm (Hayden 1934; Moore 1975). Consequently, vegetative spread is often rapid, which can lead to the production of a large amount of phytomass over a relatively short period of time. Additionally, Canada thistle is adapted to a wide range of ecological conditions, and may inhibit neighboring plant growth through allelopathy (Bendall 1975; Stachon and Zimdahl 1980; Wilson 1981). All of these characteristics contribute to the competitiveness of this species.

Canada thistle control methods in pastures and perennial forages include biological control agents, grazing, mowing, chemicals, and fertilization to enhance crop competition. Utilized individually, these methods have resulted in varying levels of thistle control (Donald 1990). However, greater, longer-term thistle control in pastures or rangeland may be achieved by combining two or more of these treatments into an integrated management strategy (Apple and Smith 1976; Zimdahl 1999; Sutherland 2001). Emphasizing the use of multiple, complimentary or synergistic control measures rather then a single technology to achieve weed management goals, this approach is often referred to as "integrated pest management" (IPM). IPM has been defined as "the coordinated use of multiple tactics to assure stable ecosystem function and maintain pest damage below economic levels, while minimizing hazard to humans, animals, plants, and the environment" (Masters and Sheley 2001). This strategy also emphasizes knowledge of invasive plant biology and ecology, and bases management decisions on ecological principles.

The initial step in any IPM plan is to assess the biological and/or economic impact of the target pest. Information from Alberta on the detrimental effect of Canada thistle on cereal and oilseed (e.g., O'Sullivan et al. 1982; 1985), as well as alfalfa (e.g., Moyer et al. 1991) seed yields is well documented, but to our knowledge, Canada thistle impacts on pasture forage biomass have not been reported in western Canada. This important initial step in the process of thistle management in pastures and hay land (i.e., quantification of yield loss) is needed to provide the rationale required by ranchers and extension personnel to develop proactive integrated thistle control strategies.

Published data on combining different methods of Canada thistle control, including herbicide application and fertilization to simultaneously enhance forage crop competition, does not appear to exist in western Canada. Additionally, the use of innovative, herbicide-delivery technology such as weed-wipers may prove useful for Canada thistle suppression in pastures where desirable broad-leaved plants such as legumes are found, but has not been reported under western Canadian growing conditions in the current literature. Compared to spraying, wiper-applicators have environmental benefits, such as reduced herbicide drift, and less damage to non-target, desirable species, and may have economic advantages, such as less damage to legumes and lower cost, as the amount of herbicide used is proportional to the amount of weeds treated (Wyse and Habstritt 1977; Moomaw and Martin 1990). Results of these types of efforts in Canada thistle control within pastures and forage crops have been reported from other regions, but appear to vary depending on the specific environmental conditions (e.g., climate, geographical area, forage species present) and prevalent management practices. Because of this, original research is needed from western Canada to evaluate the impacts of

Canada thistle in pastures and hay land, along with the effectiveness of various control strategies.

1.2 Research Objectives

The specific objectives of this research were to:

(1) Review the information available on Canada thistle biology, ecology, and control in pastures and hay land (Chapter 2),

(2) Conduct yield loss assessments to quantify forage losses caused by Canada thistle in Alberta pastures (Chapter 3),

(3) Evaluate the effects of one-time mowing or herbicide application, with and without annual spring fertilization, on Canada thistle abundance, forage yield and quality, as well as pasture vegetation composition over a 3-year period (Chapter 4),

(4) Investigate the impacts of wiper-applied herbicides on thistle abundance and pasture forage production and composition (Chapter 5), and

(5) Develop control recommendations (Chapter 6).

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2. LITERATURE REVIEW

2.1 Canada Thistle [*Cirsium arvense* (L.) Scop.]

Canada thistle is a perennial weed found in all types of agricultural land, including rangeland, pastures, and hay land. It is one of the most troublesome weeds of North America, and is classified as noxious under the Alberta Weed Control Act (Government of Alberta 2001).

2.1.1 Taxonomy

Canada thistle belongs to the Asteraceae family, and is also known as Californian thistle, creeping thistle, cursed thistle, field thistle, and perennial thistle (Holm et al. 1977). Four varieties (var. *vestitum* Wimm. & Grab., var. *integrifolium* Wimm. & Grab., var. *arvense* and var. *horridum* Wimm. & Grab.) have been recognized and separated based on variation in leaf characteristics using a key developed by Moore and Frankton (1974). All four varieties are interfertile, with the *horridum* variety being the most common and found throughout the range of this species in Canada. In Alberta, only var. *integrifolium* and var. *horridum* have been documented, but all four varieties are likely to occur there (Moore 1975). In both Europe and Canada, all varieties have been found to have a chromosome number of $2n = 34$ (Moore 1968; Moore and Frankton 1974).

2.1.2 Biology

Several comprehensive life histories and botanical descriptions of Canada thistle have been reported. These include studies from England (Hamdoun 1967), the Netherlands (Bakker 1960), and the United States (Detmers 1927; Hayden 1934; Hodgson 1968; Holm et al. 1977).

In Canada, Moore (1975) reviewed the biology of Canada thistle. He described it as a perennial herb that spreads rapidly through the production of creeping horizontal roots, which give rise to aerial shoots. The stems of Canada thistle are generally 30 to 90 cm in height, but can be as tall as 150 cm. They are slender, leafy, branched, and terminated by anywhere from 1 to 5 sessile heads. The leaves are alternate, sessile and clasping, and generally oblong in outline. Leaf margins vary from entire to deeply pinnately segmented; they can have short, fine spines or long, prominent spines varying in abundance. The upper leaf surface is glabrous, while the lower surface can be glabrous, lightly arachnoid or tomentose. Canada thistle plants are dioecious, with all heads of a plant being either male or female. Flower heads are 15 to 25 mm long, and $^1/_3$ to $^1/_4$ as wide. Male flower heads are globular in shape, and generally smaller than the female heads, which are more flask-shaped. Florets are all tubular, and vary in color from purple to pinkish to white (less common). Florets of male heads are 12 to 14 mm long, while the florets of female heads are 23 to 26 mm long. Seeds are achenes with a copious, white, feathery pappus; they are 2.5 to 4 mm long, 1 mm wide, and are straw or light brown in color.

The perennial nature of Canada thistle arises from its ability to survive indefinitely through its root system. Above-ground shoots are killed every year with

heavy frost, but plants survive the winter because of the carbohydrate-rich roots (Moore 1975). Shoots generally emerge each spring (often mid-May in Alberta) after soil and air temperatures have warmed (Alberta Agriculture, Food, and Rural Development 1984). In Montana, Hodgson (1968) found shoot emergence did not occur until mean weekly air temperatures reached 5°C, with the greatest emergence when mean weekly temperatures were 8°C. Shoots were observed to begin to emerge in early May, followed by the formation of rosettes. Rapid vertical growth began about 3 weeks following emergence, and peaked in the last 2 weeks of June, with growth averaging as much as 3 cm a day. The growth rate decreased to almost zero by the beginning of August. In general, maximum growth of Canada thistle occurs at temperatures from 15 to 25°C (Alberta Agriculture, Food, and Rural Development 1984).

Canada thistle flowers are insect-pollinated. Honey bees are the primary agent, although other insects may visit the attractive, sweet-smelling flower (Moore 1975). Because Canada thistle is dioecious, male and female plants must be physically close to each other in order for viable seeds to be produced. For example, in northern Iowa, Hayden (1934) found that when male and female plant colonies were 8 to 30 m away from each other, a substantial number of viable seeds were produced (20 to 30 seeds per head). When the distance between male and female colonies increased to 150 to 180 m, few seeds were found (only 2 or 3 per head). While up to 30,000 viable seeds m^{-2} have been found within a thistle stand (Amor and Harris 1974), few seeds are formed unless male and female plants are less than 50 to 90 m apart (Hayden 1934; Bakker 1960). However, Amor and Harris (1974) did report that some seed was produced when male

and female plants were as far apart as 390 m. While male Canada thistle plants may form viable seeds on their own (Hodgson 1968), this is not a common occurrence.

Moore (1975) reported that as many as 83 to 98 seeds were produced per head, and that viable seeds were fully developed 8 to 10 days after flowering. One plant may produce up to 5,300 seeds, with the average production 1,530 seeds. Hodgson (1968) found wide variation in seed size among ecotypes, with the smallest equal to 677,000 seeds per pound, and the largest equal to 298,000. The average seed weight found in a three-year study of eight ecotypes in Montana was 0.096 g per 100 seeds (Hodgson 1968).

Canada thistle seeds have a plumose achene, making wind the main means of dispersal. However, there is evidence of other long-distance seed dispersal methods, such as water, as Canada thistle seeds have been found in irrigation water in Alberta (Moore 1975).

Although some authors have reported that Canada thistle seed requires a dormancy period, the majority agrees that a dormancy period is not required for germination to occur (Moore 1975). Germination is greatest at air temperatures of 25 to 30°C, and is aided at lower temperatures (15 to 20°C) by high light intensity (Bakker 1960; Moore 1975). Amor and Harris (1974) found that seed from 37 sites in Australia, stored at 20°C for 6 months, had an average germination of 78% (range 52 to 97%). The germination was tested at 15 / 30°C with a 12 hour photoperiod. Hayden (1934) reported that freshly gathered seed (collected in August in Iowa) had a germination as high as 95%. Hodgson (1964) found that fresh seeds had a germination of 50 to 80%. Moore (1975) summarized a number of studies which found the following germination rates: 42 to 66%

after dry storage at room temperature (Derscheid and Schultz 1960); 62% after 8 months dry storage, 25% after 12 months dry storage, 70% after 6 months submergence in water (Bruns and Rasmussen 1957); and 38 to 71% (average 50%) after two years of dry storage (Hayden 1934). Toole and Brown (1946) found up to 26% viability of Canada thistle seeds after 6 years, 5% viability after 21 years, and 0% viability after 30 years.

Hayden (1934) noted that germination occurs immediately after seed dissemination in July or August. By winter, rosettes may develop with a root system sufficient to support flowering in spring. Canada thistle seeds that do not germinate in the fall may germinate in spring, and these plants will likely flower in the second season. Seeds left lying in flats in the green house or on the ground were found to germinate at successive intervals, rather then all at once (Hayden 1934). This staggered germination resulted in plants growing at different stages of development, which likely contributes to the competitiveness of Canada thistle (Hayden 1934).

Canada thistle is a long-day plant; flowering in Canada occurs in mid-June or early July, and continues into September. Thistle plants require an 18-hour light period for flowering to take place, and will not flower under 8 to 12 hour days (Moore 1975). Hunter and Smith (1972), in their study of seven Canada thistle ecotypes, found that flowering occurred in all ecotypes under a 16-hour photoperiod. Under a 14-hour photoperiod, five ecotypes flowered, with flowering in three of them temperature-dependent.

The importance of seed production in the survival and propagation of Canada thistle is uncertain. While earlier studies of Canada thistle placed a great importance on the spread of Canada thistle through seed production and dispersal (e.g., Hodgson 1968),

more recent studies assert that vegetative reproduction is the chief means of propagation (e.g., Nadeau 1988; Donald 1990). Vegetative reproduction occurs in two ways: (1) the underground shoots can produce buds at all nodes and roots at any point, and (2) horizontal and vertical roots are able to produce shoots or roots at any point (Hayden 1934; Nadeau 1988). While the first means of vegetative spread can result in the production of many new plants, it is the second that has the capacity to produce the greatest number of plants per unit mass. This is because stem fragments will have buds at intervals of 2.5 to 5 cm, while adventitious root buds can produce new shoots anywhere along the length of roots. Shoot development has been reported from 14% of root fragments 3 to 6 mm thick and 8 mm in length, while 100% of root segments 12.5 mm in length developed shoots (Hayden 1934; Moore 1975).

Hodgson (1968) examined the distribution of Canada thistle roots in the soil profile. Root sampling of newly established Canada thistle plants at three depths revealed 54% of roots (by dry weight) were within the top 7.5 to 22.5 cm of soil; 30% were 22.5 to 37.5 cm below the surface; and 16% were 37.5 to 52.5 cm below the surface. The author suggested that an older stand would likely have a greater percentage of roots deeper in the soil. Nadeau (1988) found a quarter to a third of total root length and root dry matter, and half of the total root bud production, were in the top 20 cm of soil. Roots commonly penetrate to depths of 2 to 3 m, and have been found as deep as 6.75 m (Hodgson 1968; Moore 1975; Nadeau and Vanden Born 1989). Horizontal root spread can be as much as 6 m in one season (Moore 1975). In pastures, Amor and Harris (1975) reported that established patches of Canada thistle spread vegetatively by as much as 3.4 m in one year, with an average annual spread of 1.5 m.

In Montana, root carbohydrate reserves (percentage of dry weight) were lowest in early June, which coincided with the early bud stage of growth (i.e., buds just beginning to form; Hodgson 1968). From June onwards, carbohydrate reserves increased steadily and then leveled off in September. Similar findings were summarized by Moore (1975).

2.1.3 Habitat and Distribution

Canada thistle is found in cultivated fields, meadows, pastures, hay land, rangeland, roadsides, waste areas, railway embankments, lawns, gardens, and virtually any plant community that has been in contact with humans (Moore 1975; Frankton and Mulligan 1987). It thrives in areas with moderate summer temperatures (0 to 32°C), and rainfall of 400 to 900 mm per year. Adapted to a wide range of soils, Canada thistle has been collected in clay loams, sandy loams, sandy clays, silt loams, and even sand dunes (Hodgson 1968; Moore 1975). Well-aerated soils support good thistle growth while poorly aerated soils or high water tables limit growth (Hodgson 1968). Although found on the banks of streams, edges of wetlands, lakeshores, and wet ditches, it does not survive in very wet locations. There is some evidence that Canada thistle is tolerant to soil salinity, as it has been found in soils with a salt content up to 2% (Donald 1990). Thistle was found in 40% of nonmarsh, dry saline sites surveyed in Alberta (Braidek et al. 1984). Although the species generally prefers moist locations, it is occasionally found in dry habitats such as sand dunes and open sandy areas. Another requirement for growth is adequate light intensity. With excessive shade, thistle plants can become tall and lax and produce few flowers (Moore 1975).

The precise origins of this species are not known for certain, but it is believed to be endemic to Europe, western Asia, and northern Africa (Hayden 1934; Hodgson 1968; Donald 1990). Moore (1975) suggested that its origins lie in southeastern Europe and the eastern Mediterranean. Regardless of where it originated, Canada thistle is now found throughout most temperate regions of the world. In the northern hemisphere it is found in Europe, North Africa, central and northern Asia, as well as North America. It extends north to 68° in Scandinavia, and has been observed in northern Siberia, but reportedly does not flower north of 58° latitude (Hayden 1934). It extends as far south as 30°N latitude in North Africa and Afghanistan. It has also spread to the southern hemisphere, where it has become problematic in South America, South Africa, New Zealand, and Australia (Moore 1975).

It is believed that Canada thistle was introduced to North America by Europeans as an impurity in farm seed, and was well established in both French and English colonies by the late 1700's (Hayden 1934; Moore and Frankton 1974). The first legislation to control Canada thistle was passed in Vermont in 1795, and the species was reportedly common in Montreal by 1821.

In the UK, it has been cited as the "most widespread, troublesome, and difficult to control" of all weeds found in grassland (Haggar et al. 1986). It reportedly infests approximately 1 million ha of grassland in England and Wales.

In the United States, Canada thistle is widespread north of approximately 37°, but does not survive in the southern states, likely owing to the fact that it is a long-day plant and does not grow well under high summer temperatures (Moore 1975). It is most prevalent in the north-western and north-central states (Moore and Frankton 1974), and

was considered a common and troublesome weed in pasture and hay land in six of nine western U.S. states surveyed (Donald 1990). Skinner et al. (2000) identified the most commonly regulated weedy plants in the United States and Canada. The authors compiled a database of noxious weed lists from the 48 continental states and the six provinces bordering the United States, and summarized the 45 most frequently listed noxious weeds. Canada thistle was ranked as the most frequently listed weed, being found on 33 noxious weed lists.

Canada thistle is found in all provinces in Canada as far north as 59° (Moore 1975). In provincial weed surveys carried out across Canada between 1922 and 1947, Canada thistle was found in 39 to 83% of all agricultural districts surveyed (Dew 1981). Another Canada-wide weed survey conducted from 1963 to 1964 reported that Canada thistle was found in almost every municipal unit surveyed, with most units having medium or heavy infestations (Alex 1966). In Alberta alone, as many as 4 million hectares were found to be infested with Canada thistle. Thomas et al. (1998) carried out more recent weed surveys in Alberta, focusing on cereal and oilseed crops. In the first survey (from 1987 to 1989), Canada thistle was found in 35% of 1113 fields examined, and was ranked 12th in relative abundance among 166 different weed species. In the second survey (1997), Canada thistle was found in 53% of 684 fields examined, and was ranked 4th highest in relative abundance among 110 different weed species, suggesting a possible increase in prevalence from a decade earlier. Comprehensive weed surveys in forage crops have not been conducted in Canada (Dan Cole pers. comm.), but Moyer et al. (1991) stated that Canada thistle was present in 90% of the irrigated alfalfa seed fields in southern Alberta. The limited weed surveys that have been carried out in forage crops

of the Peace River Region of British Columbia (Thomas and Wise 1983), and in Manitoba (Goodwin et al. 1986), have shown that Canada thistle can be as problematic as in other agricultural crops.

2.2 Nature of the Problem

Canada thistle is considered an important agricultural weed for a number of reasons. First, it is adapted to a broad range of ecological niches (Moore 1975; Donald 1990). Second, the aggressive, extensive creeping root system allows it to spread rapidly and produce a large amount of phytomass over a relatively short period of time. As a result, water, light, nutrients, and space are utilized, impacting crop yields. Third, there is evidence that Canada thistle may exhibit allelopathy, the suppression of growth of one plant species by another due to the release of toxic substances (Bendall 1975; Stachon and Zimdahl 1980; Wilson 1981). As a result of these biological properties (adaptability, rapid vegetative spread, and potential phytoxicity), Canada thistle is highly competitive in a wide range of crops. These include barley, oats, rye, wheat, sorghum, canola, flax, millet, beans, peas, and forages (Moore 1975; Donald 1990).

A large body of literature exists with respect to Canada thistle research in cereals and oilseeds (e.g., Alberta Agriculture, Food, and Rural Development 1980), but relatively few studies have examined Canada thistle in a pasture or hay land setting. This is despite the fact that Canada thistle has been cited numerously as a detrimental weed of pastures and perennial forage crops in northern Europe (Holm et al. 1977; Haggar et al. 1986), Australia and New Zealand (Amor and Harris 1974, 1975; Hartley and James

1979), the United States (Schreiber 1967; Hodgson 1968), and Canada (Hay and Ouellette 1959; Goodwin et al. 1986; Moyer et al. 1991).

While early researchers suspected that Canada thistle caused pasture forage yield loss (e.g., Hodgson 1968), priority was given to yield loss assessments in cultivated land. Hodgson (1955, 1968) found that 13 to 20 Canada thistle shoots·m^{-2} caused yield reductions of 30% in winter wheat, 29 to 60% in spring wheat, 40% in barley, and 62% in oats. In central Alberta, 20 Canada thistle shoots·m^{-2} reduced canola yields by 26%, barley yields by 34%, and wheat yields by 51% (O'Sullivan et al. 1982; 1985). In North Dakota, Donald and Khan (1992; 1996) found significant yield reductions of semidwarf hard red spring wheat caused by Canada thistle. More recently, Mamolos and Kalburtji (2001) in northern Greece found 16 Canada thistle shoots·m^{-2} reduced wheat yields by 19%. While yield losses are often related to weed density only (e.g., O'Sullivan et al. 1985; McLennan et al. 1991), Hume (1985) reported spring wheat yield was better estimated by annual weed shoot dry weight·m^{-2} than annual weed density. In contrast, no difference was found between Canada thistle density and shoot dry matter biomass·m^{-2} for predicting barley (O'Sullivan et al. 1982) and wheat (Donald and Khan 1992) yields.

In forage crops, Moyer et al. (1991) found that alfalfa seed yield loss due to Canada thistle in irrigated fields of southern Alberta was well within the range of yield reductions observed in cereal and oilseed crops. At thistle densities of 10 and 20 shoots·m^{-2}, yield losses were >34% and >48%, respectively.

Canada thistle can negatively impact pasture production directly and indirectly. First, it may directly compete with the pasture plant species and cause measurable yield reductions. Second, its prickly growth habit may discourage grazing by livestock,

thereby reducing the size of the grazeable area. Schreiber (1967) attempted to measure these two aspects of Canada thistle impacts in alfalfa pasture. Over the course of 4-years in Indiana, Schreiber (1967) found that two thistle shoots per 0.09 m^2 reduced alfalfa yield by 17 $mt \cdot ha^{-1}$. In addition, alfalfa consumption by sheep was reduced by an estimated 10 $mt \cdot ha^{-1}$. Schreiber (1967) attributed the reduced utilization to the physical presence of Canada thistle. Further evidence of the negative impacts of Canada thistle on utilization by grazing livestock has been reported from New Zealand with sheep and cattle (Hartley and James 1979). Unfortunately, there have been no further efforts to assess pasture forage yield loss due to Canada thistle, which has left a gap in our knowledge base.

Canada thistle is particularly problematic in pastures and hay land in central Alberta for a number reasons. As noted earlier, it has the capacity to reduce pasture forage yields, either directly through competition, or indirectly through impaired grazing. Second, it can be more difficult to control in pasture or hay land compared to cultivated crops where tillage and a wide range of herbicides can be employed. Third, there is often a perceived disincentive to pro-actively manage weeds by livestock producers, which arises from the lower value placed on pasture and hay land compared to cultivated cropland. When producers fail to use the tools of more intensive pasture management, such as herbicides, fertilizer, deferred grazing, and rotational grazing, Canada thistle infestations can increase unchecked until the only viable solution is to break-up the land and re-seed.

Canada thistle is listed as a noxious weed under the Alberta Weed Control Act (Government of Alberta 2001). The process by which a weed is added to a noxious weed

list involves committees comprised of individuals from government, private industry, and local jurisdictions that use a set of criteria to assess whether or not a weed should be listed. These criteria include, among others, the acreage infested, the potential habitat types susceptible to invasion, potential negative impacts (economic and environmental), number of national and international listings, and biological characteristics (Sheley and Krueger 1999). The noxious weed designation of Canada thistle in Alberta enables local and provincial jurisdictions to enforce its control, which underscores its social and agronomic importance.

2.3 Control of Canada thistle

Donald (1990) reviewed the literature pertaining to the control of Canada thistle. Documented methods of control include cultivation, biological control, mowing, grazing, herbicides, and fertilizer and crop competition. The future potential for longer-term control of Canada thistle in pastures and hay land will most likely be achieved through some combination of these control measures into an integrated pest management (IPM) strategy (Trumble and Kok 1982; Masters and Sheley 2001). Integrated pest management has been defined as a sustainable approach to plant, animal, human, and structural protection that combines educational, cultural, physical, biological, and chemical strategies to minimize losses due to pests (insects, diseases, and weeds) and to minimize environmental and health impacts (Apple and Smith 1976; Manitoba Agriculture 1995; Zimdahl 1999).

2.3.1 Cultivation

The use of tillage to control Canada thistle in annual cropping systems has been well documented (e.g., Detmers 1927; Hodgson 1955, 1968, 1970; Derscheid et al. 1961), and has generally been successful, with some exceptions (e.g., Zimdahl and Foster 1993). Repeated cultivation destroys the new shoots and leaves of thistle plants, which prevents the build up of root carbohydrate reserves. In turn, new shoot emergence is inhibited, which further limits carbohydrate accumulation (Hodgson 1968). Notably, the actual biochemical and physiological mechanisms behind reductions in root biomass caused by tillage are largely unknown (Donald 1990). There are problems associated with cultivation, including the increased likelihood of soil erosion, the possibility of tillage not reaching deeper thistle roots, and the potential for spreading Canada thistle across fields, as very small root fragments (e.g., as short as 8 to 12.5 mm) can give rise to new thistle shoots.

2.3.2 Biological Control

The use of biological control agents to suppress Canada thistle has met with limited success (Trumble and Kok 1982; Donald 1990). Studies by McClay (1993), Ang et al. (1994a,b; 1995), Bourdot et al. (2000, 2001), and Hoeft et al. (2001) have shown some promise. For example, the European stem-mining weevil, *Ceutorhynchus litura*, was reported to reduce the production of new thistle shoots from overwintered underground buds, suggesting the possible utility of the insect in reducing vegetative spread (McClay 1993). The use of the fungal pathogen *Sclerotinia sclerotiorum* as a mycoherbicide in the suppression of Canada thistle in New Zealand pastures has also

shown some potential (Bourdot et al. 2000, 2001). Gronwald et al. (2002) also reported some success in the use of *Pseudomonas syringae* pv. *tagetis* as a biological control agent for Canada thistle.

Ang et al. (1994b, 1995) combined plant competition from tall fescue, (*Festuca arundinacea* Schreb.), and crownvetch, (*Coronilla varia* L.) with a thistle defoliator, *Cassida rubiginosa* Müller, to suppress the growth of Canada thistle. When combined, the two control strategies gave better thistle control than either one on its own, which underscores the value of integrated approaches to controlling Canada thistle. Other studies, including those of a rust fungus (Thomas et al. 1994) and a phytopathogenic bacterium (Hoeft et al. 2001) have demonstrated the ability of biological agents other than insects to negatively impact thistle growth and survivorship, which could also have applications in integrated weed management.

More recently, Friedli and Bacher (2001) and Bacher et al. (2002) have explored the mutualistic relationship between the shoot-base boring weevil *Apion onopordi* Kirby and the rust fungus *Puccinia punctiformis* (Str.) Röhl, both parasites of Canada thistle. These studies have largely focused on their ecological relationship, but there may be future potential for the integration of these two species into a biological control strategy for Canada thistle.

2.3.3 Mowing

Frequent mowing has been shown to greatly reduce Canada thistle infestations in forage stands such as alfalfa or legume and grass mixtures (Detmers 1927; Welton et al. 1929; Hodgson 1958, 1968; Amor and Harris 1977; Hartley and James 1979). Although

studies to date have not examined the underlying physiological or biochemical mechanisms behind the control of Canada thistle through mowing, Detmers (1927) summed up essentially what is hypothesized today. That is, mowing likely serves not only to prevent seed formation, but also to weaken the thistle plant by reducing the amount of carbohydrates assimilated by leaves and green stems, and therefore, the amount of carbohydrate reserves stored in roots. Detmers (1927) recommended that in order to kill the plant, the first cutting should be carried out when thistles are small, and that subsequent cuttings should follow at short intervals (e.g., every 1 to 2 weeks).

The frequency and timing of mowing determine the effectiveness of control. Mowing twice (Hodgson 1958, 1968), two to three times (Schreiber 1967), and three to four times (Welton et al. 1929) per year for three to four years reduced Canada thistle infestations in alfalfa hay fields. Alfalfa mowed biannually for three years proved highly effective in controlling Canada thistle in Montana (Hodgson 1958) and Indiana (Schreiber 1967). In the latter case, Canada thistle was artificially established at three densities, and control was achieved most rapidly with the lowest initial shoot density. This suggests that initial Canada thistle shoot densities influence the success of suppression with mowing.

It has been recommended that the timing of initial mowing coincide with the early part of the growing season (e.g., early or mid June), and then continue at 1-month intervals. However, very frequent mowing (e.g., 3 or more mowings per season) would likely limit forage production, defeating its value as a control measure. Also, little research has looked at long-term effects, so reinfestation rates and the persistence of control are unknown. Amor and Harris (1977) found that on its own, infrequent mowing

(e.g., mowing once each year) did not provide significant longer-term control of Canada thistle. The usefulness of occasional mowing as a control measure on its own is doubtful.

Attempts to separate the effectiveness of grass competition from mowing have shown that seeded perennial grasses were as good as or better than biannual mowing for the control of Canada thistle (Wilson and Kachman 1999). However, there may be utility in combining mowing with the seeding of competitive forage crops as an integrated approach to controlling Canada thistle. For example, both perennial grasses and alfalfa have been shown to suppress Canada thistle when combined with mowing (Hodgson 1958; Derscheid et al. 1961; Thrasher et al. 1963). Smooth bromegrass (*Bromus inermis* Leyss.) establishment combined with mowing reduced Canada thistle by greater than 90% over three years (Derscheid et al. 1961), while tall fescue coupled with mowing suppressed Canada thistle densities by 60 to 70% over three years (Thrasher et al. 1963).

2.3.4 Grazing

Few studies have looked at the effectiveness of grazing compared to mowing for the control of Canada thistle. In the early 1900's, sheep and goats were apparently successful in keeping Canada thistle in check, and as a result, were recommended for its control in pastures (Donald 1990). According to studies of thistles belonging to the genus *Carduus*, continuously grazed pastures are more susceptible to thistle development than rotationally or ungrazed pastures (Feldman et al. 1968; Bendall 1973). Because thistles are pioneer species, they tend to establish and spread more readily with the increased bare ground and reduced canopy cover that can result from overgrazing. When herbage cover and biomass increase with decreased grazing pressure, there is a

corresponding decline in the number of thistle seedlings per ha (Trumble and Kok 1982; Edwards et al. 2000). The effects of livestock grazing on Canada thistle in Alberta pastures have not yet been published.

2.3.5 Herbicides

Herbicides have been the most extensively studied of all Canada thistle control methods, and while more information is available on annual cropping systems than pasture or hay land, both have received attention and were reviewed by Donald (1990). In general, the recommended time for spraying Canada thistle is in early summer when the plant is in the bud stage and carbohydrate root reserves are low. The magnitude and duration of efficacy, the degree of damage to desirable species such as legumes, and the cost/benefit of application determine the usefulness of herbicides in controlling thistle in forages. Selective, broad-leaf herbicides used for Canada thistle control include, but are not limited to, 2,4-D, (2,4-dichlorophenoxy acetic acid), dicamba, (3,6-dichloro-2-methoxybenzoic acid), picloram, (4-amino-3,5,6-trichloro-2-pyridinecarboxylic acid), and clopyralid, (3,6-dichloro-2-pyridinecarboxylic acid).

Greenhouse and field studies have shown that both 2,4-D and dicamba are mobile primarily in the leaves and shoots, and therefore affect mainly the above-ground component of Canada thistle, while picloram and clopyralid provide greater, longer-term control through suppression of root growth (Hunter and Smith 1972; O'Sullivan and Kossatz 1982; Turnbull and Stephenson 1985). Compared to 2,4-D, dicamba controls Canada thistle more effectively and for longer periods due to its ability to move throughout the plant more readily and cause greater tissue damage (Chang and Vanden

Born 1968, 1971; Hunter and Smith 1972). The effectiveness of picloram has been attributed to both its ability to enter and translocate through the plant very rapidly, enhancing its ability to severely damage the root system, and its persistence in the soil (Vanden Born 1969; Sharma et al. 1971). Owing to their closely-related chemical structures, clopyralid effects on Canada thistle are similar to picloram, with the exception that clopyralid soil persistence is shorter, resulting in fewer restrictions on its use (O'Sullivan and Kossatz 1984; Turnbull and Stephenson 1985; Alberta Agriculture, Food, and Rural Development 2003).

Although Canada thistle can be suppressed with 2,4-D, repeated applications of 2,4-D ester at 1.12 $kg \cdot ha^{-1}$, one in the spring and another in the fall, for three years, were needed to significantly reduce thistle densities in Ontario pastures (Hay and Ouellette 1959). In an alfalfa pasture in Indiana, yearly applications of 2,4-DB, 4-(2,4-dichlorophenoxy) butanoic acid at 1.12 $kg \cdot ha^{-1}$ at the early bud stage of growth over 5 years were required to almost eradicate Canada thistle (Schreiber 1967). Other studies (e.g., Gallagher and Vanden Born 1976; Amor and Harris 1977) are in agreement with the notion that 2,4-D is useful in thistle suppression, but is limited in its ability to eradicate Canada thistle.

In Nebraska pastures, 2,4-D, dicamba, clopyralid, and picloram at rates ranging from 0.3 to 1.1 $kg \cdot ha^{-1}$ applied in various sequences all significantly reduced Canada thistle density and biomass (Reece and Wilson 1983). However, because of the combined treatment structure, it was not possible to separate the effects of individual herbicides. When averaged, all herbicides increased grass production by 110, 314, and 212 % per year over 3 years, which illustrates the added benefit that spraying may

provide. Mowing followed by fall herbicide application in Colorado pastures showed that picloram and picloram+2,4-D were most effective in controlling Canada thistle, followed by dicamba and clopyralid+2,4-D (Beck and Sebastian 2000).

Both herbicide efficacy as well as the tolerance of desirable forages to herbicides are important considerations in determining the utility of herbicides in forage crops. For example, in Canada thistle infested grass seed crops of creeping red fescue (*Festuca rubra* L.) and timothy (*Phleum pratense* L.) in Alberta, treatment with picloram (0.14 to 1.12 $kg \cdot ha^{-1}$) resulted in significantly lower Canada thistle shoot densities than either 2,4-D ester (1.12 $kg \cdot ha^{-1}$) or dicamba (0.56 to 2.24 $kg \cdot ha^{-1}$; Gallagher and Vanden Born 1976). While dicamba usually provided better control than 2,4-D ester, these effects were not as consistent as picloram efficacy (Gallagher and Vanden Born 1976). Neither grass species was significantly damaged by the herbicides. In pastures dominated by white clover (*Trifolium repens* L.) and perennial ryegrass (*Lolium perenne* L.) in Australia, broadcast spraying with 2,4-D amine or 2,4-D ester, each at 4 $kg \cdot ha^{-1}$, did not reduce Canada thistle shoot densities, while picloram+2,4-D at 0.5 $kg \cdot ha^{-1}$ gave significant control lasting two years (Amor and Harris 1977). However, picloram+2,4-D also eliminated white clover from the sward, which did not recover during the last two years of the study. Spot applications of picloram+2,4-D significantly reduced the cover of white clover, but did not completely eliminate it, and 1 year following treatment, the clover had begun to recover.

Peterson and Parochetti (1978) found similar trends in a timothy and red clover (*Trifolium pratense*) sward in Maryland. Picloram at 0.56 and 1.12 $kg \cdot ha^{-1}$ eliminated red clover the first year, and provided between 95 and 100% control of Canada thistle three

years following treatment, likely because of its lengthy persistence in the soil (Peterson and Parochetti 1978). Dicamba at 1.12 kg·ha^{-1} reduced red clover by 57 to 87% and Canada thistle by 72% in the first year, but did not provide longer-term thistle control. Both the amine and ester versions of 2,4-D at 1.68 kg·ha^{-1} gave variable thistle control, but reduced the red clover by only 10 to 15%. There was no effect on grass yield.

Because picloram can persist in the soil for up to 5 years, spot or selective applications may be more useful than broadcast spray applications in pastures that contain legumes (Alberta Agriculture, Food, and Rural Development 2003). Selective application with a weed wiper is one method that damage to desirable forage species could be reduced, and could have the added benefits of reducing herbicide drift and lessening the amount of herbicide used per hectare (Wyse and Habstritt 1977; Moomaw and Martin 1990). Wiper applicators come in a number of forms, including rope-wicks, rollers, and sponges, and they function by wiping herbicide solution directly onto weeds that are taller than the forage crop.

Wiper-applied non-selective herbicides such as glyphosate, *N*-(phosphonomethyl) glycine, as well as selective broadleaf herbicides may prove useful in controlling thistle in grazed pastures. Results from studies of brush (Mayeux and Crane 1983, 1984; Gibson et al. 1984; Mayeux 1987; Waddington and Bittman 1987a, b; Bovey and Meyer 1989), dandelion, *Taraxacum officiniale* Web., and leafy spurge, *Euphorbia esula* L. control (Messersmith and Lym 1985; Welker and Peterson 1989; Moomaw and Martin 1985, 1990) vary, but generally support the utility of wiper applicators for brush and weed control. For example, a carpeted roller applicator was used in northeastern Saskatchewan to provide 1 to 3 year control of aspen (*Populus tremuloides* Michx.),

balsam poplar (*Populus balsamifera* L.), and willow (*Salix* spp.) regrowth (Waddington and Bittman 1987a). Glyphosate at 0.53% a.i., and 2,4-D+picloram at 0.60 + 0.07% a.i., provided better control than 2,4-D at 0.25 to 6.75% a.i. (Waddington and Bittman 1987a).

Until recently, few wiper studies had specifically addressed Canada thistle control in forages. In birdsfoot trefoil (*Lotus corniculatus* L.) seed fields in Minnesota, Boerboom and Wyse (1988) reported that 10 and 33% (v/v) solutions of commercial herbicide formulations of picloram, clopyralid, and glyphosate reduced Canada thistle infestations more than wiped solutions of MCPA and dicamba. Picloram, clopyralid, and dicamba injured trefoil, while glyphosate and MCPA did not. More recently, in a smooth bromegrass dominated riparian pasture in Montana, Krueger-Mangold et al. (2002) found that two consecutive years of wick-applied glyphosate at 1.5, 3.0, and 4.5 $kg \cdot ha^{-1}$ significantly reduced Canada thistle density and biomass compared to the untreated check. Presently, there is no published research on the utility of weed-wipers for controlling Canada thistle in western Canadian pastures.

2.3.6 Fertilization and Competition

Canada thistle, like other weeds, competes with desirable plant species for space, light, moisture, and nutrients. The easiest of these factors to manipulate in non-irrigated pasture and hay land is nutrients, which can be added through surface applied fertilizer. Nitrogen fertilization can improve forage quantity and quality, and enhance the competitive ability of desirable forage species, mainly grasses, with weeds (Hay and Ouellette 1959). Competition among species, or "interspecific competition", is said to occur when "individuals of one species suffer a reduction in fecundity, survivorship or

growth as a result of resource exploitation or interference by individuals of another species" (Begon et al. 1990). Desirable forage species may respond better to added nutrients because of differences in the timing of nutrient uptake and utilization, access of nutrients to roots, or other unknown factors, resulting in increased cover and yield, and therefore, enhanced competitiveness (DiTomaso 1995). Fertilization, either alone or in combination with other control measures, has proven effective with some weeds in forage crops, including spotted knapweed (*Centaurea maculosa* L.) in rangeland (Sheley and Jacobs 1997) and ox-eye daisy (*Chrysanthemum leucanthemum* L.) in pastures and hay land (Cole 1998).

In contrast, the addition of nutrients may favor weed growth over crop growth, particularly when initial weed density is high (DiTomaso 1995). For example, Canada thistle may be more problematic in nitrogen-fertilized stands than in non-fertilized stands, as its shoot production has been shown to increase with nitrogen fertilization (Hamdoun 1970; Nadeau 1988; Nadeau and Vanden Born 1990). However, Canada thistle root bud growth may also decrease with increasing nitrogen fertilization (McIntyre and Hunter 1975). Research is lacking on the effectiveness of fertilization in enhancing forage crop competition with Canada thistle. The limited information available indicates that fertilization in wheat (Hodgson 1958, 1968; McKay et al. 1959; Hume 1982) and pastures (Hay and Ouellette 1959; Thrasher et al. 1963; Reece and Wilson 1983) has mixed results. For example, surface-applied fertilizer in spring wheat reduced Canada thistle shoot densities in Saskatchewan (90 kg·ha^{-1} of 23-23-0 N-P-K; Hume 1982), increased shoot densities in Montana (56 kg·ha^{-1} N; Hodgson 1958), and had no effect on shoot densities in Idaho (90 kg·ha^{-1} N; McKay et al. 1959). Nitrogen fertilizer at 90 kg·ha^{-}

^{1} in spring wheat improved the control of Canada thistle using 2,4-D amine, compared to when 2,4-D amine was applied alone (McKay et al. 1959). However, Hodgson (1958) found that nitrogen fertilization at 56 kg·ha^{-1} combined with 2,4-D ester did not improve Canada thistle control in spring wheat compared to 2,4-D alone.

In pastures, the response of Canada thistle to fertilization has also been inconsistent. For example, ammonium nitrate at 45 kg·ha^{-1} in Nebraska pastures significantly increased Canada thistle density and biomass over three years (Reece and Wilson 1983). In contrast, high rates of nitrogen fertilization (224 and 448 kg·ha^{-1}) in irrigated Montana pastures reduced Canada thistle densities, presumably as a result of the enhanced competition by grasses (Thrasher et al. 1963). In Ontario pastures, fertilization alone (56-67-101 kg·ha^{-1} N-P-K) had no effect on Canada thistle densities, but improved forage yield when combined with 2,4-D ester (Hay and Ouellette 1959). More recently, nitrogen applied at 150 kg·ha^{-1} in acid grassland of the UK, significantly reduced Canada thistle densities (Edwards et al. 2000). The reasons for these inconsistencies are not clear, but may be due to climate, vegetation, soil type, relative competitiveness of the associated crop/forage, initial nitrogen concentration and distribution in the soil, and the form of nitrogen applied (e.g., urea or ammonium-nitrate; Donald 1990). Further basic descriptive research and ultimately, more detailed, mechanistic studies, are needed to determine whether competition between desirable forages and Canada thistle may be improved through soil fertility management.

In the absence of fertilization, competitive forages have been used to suppress Canada thistle growth. In the early 1900's, when comparisons were made among timothy (*Phleum pratense* L.), orchardgrass (*Dactylis glomerata* L.), redtop (*Agrostis alba* L.),

sweetclover (*Melilotus indica* All.) and alfalfa (*Medicago sativa* L.), alfalfa and sweetclover apparently suppressed Canada thistle more effectively than grasses (Detmers 1927). In general, alfalfa has been recommended as a forage crop to compete with Canada thistle because of its earlier emergence in spring, which enables it to form a competitive cover, and also because of its quick recovery following mowing (Hodgson 1958). In addition, cereal crop rotations that include an alfalfa hay crop often have lower Canada thistle levels than those that do not (Ominski et al. 1999). However, grasses can be effective competitors as well: comparisons of five perennial grasses in suppressing Canada thistle growth showed that hybrid wheatgrass (*Agropyron spicatum* x *Agropyron repens*) was the most effective, and that perennial grasses established using preplant rototilling were as effective in controlling Canada thistle as yearly applications of clopyralid at 0.55 $kg \cdot ha^{-1}$ (Wilson and Kachman 1999).

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3. PASTURE FORAGE YIELD LOSS DUE TO CANADA THISTLE

3.1 Introduction

Canada thistle (*Cirsium arvense* L. Scop) is one of the most widespread and problematic agricultural weeds in Canada and the northern United States (Alex 1966; Donald 1990). Skinner et al. (2000) reported it to be the most frequently listed weed based on noxious weed lists compiled from agricultural land throughout Canada and the United States. It occurs throughout Canada as far north as 59°, and was found in over 50% of all cereal and oilseed fields surveyed in Alberta during 1997 (Thomas et al. 1998). The few weed surveys of forage crops available in western Canada indicate the Canada thistle problem is severe in alfalfa (*Medicago sativa* L.) seed fields, as well as in pasture and hay land (Thomas and Wise 1983; Goodwin et al. 1986).

Early yield loss assessments lend support to the notion that Canada thistle is a highly successful competitor for moisture, light, nutrients, and space (Donald 1990). The highly competitive nature of this weed is likely a result of its adaptation to a broad range of environmental conditions and its aggressive, extensive creeping root system, which allows it to spread rapidly, producing a large amount of phytomass over a relatively short period of time (Moore 1975). Estimates of yield loss due to Canada thistle have been reported in barley, oats, and spring wheat in Montana (Hodgson 1955, 1968), spring wheat in North Dakota (Donald and Khan 1992, 1996), winter wheat in Saskatchewan and Europe (McLennan et al. 1991; Mamolos and Kalburtji 2001), and barley, canola,

and spring wheat in Alberta (O'Sullivan et al. 1982; 1985). In the latter two studies, 20 Canada thistle shoots m^{-2} significantly reduced canola, barley, and wheat yields by 26%, 34%, and 51%, respectively. Compared to annual crops, few studies have examined forage yield losses despite the fact that Canada thistle has been recognized as a major problem in pastures and perennial forages in northern Europe (Holm et al. 1977; Haggar et al. 1986), Australia and New Zealand (Amor and Harris 1974, 1975; Hartley and James 1979), the United States (Schreiber 1967; Hodgson 1968), and Canada (Hay and Ouellette 1959; Goodwin et al. 1986; Moyer et al. 1991).

The limited research that has been done in forages suggests Canada thistle infestations reduce yield (Schreiber 1967; Moyer et al. 1991). Canada thistle likely reduces pasture production directly through competition with desirable plants, although there is also evidence thistle may limit neighboring plant growth through allelopathy (Bendall 1975; Stachon and Zimdahl 1980; Wilson 1981). Over the course of four years in Indiana, 20 thistle shoots m^{-2} reduced alfalfa forage yields by 16 mt ha^{-1}, in the absence of grazing animals (Schreiber 1967). In irrigated fields of southern Alberta, Moyer et al. (1991) found Canada thistle densities of 10 and 20 shoots m^{-2} reduced alfalfa seed yields by >34% and >48%, respectively, well within the range of yield loss reported in cereal and oilseed crops. Thistle may also decrease livestock production indirectly through impaired grazing of adjacent forage caused by its spiny morphology. Both Schreiber (1967) and Hartley and James (1979) reported that Canada thistle decreased forage utilization by sheep and cattle.

At present there is no quantitative information on the forage losses occurring in perennial pastures of western Canada due to Canada thistle. This lack of information is

probably partly a result of the heterogeneity inherent to permanent pastures, which makes research more difficult than in cultivated fields, where conditions can be more easily controlled. The provision of yield loss information is generally a pre-requisite to encourage livestock producers to manage weeds. Furthermore, in order for producers to determine the minimum abundance of Canada thistle that may economically justify control, specific quantitative data on pasture forage yield loss is needed, along with practical guidelines for estimating these losses under field conditions.

The objectives of this study were to: (1) conduct yield loss assessments to quantify forage losses caused by Canada thistle in Alberta pastures, and (2) compare the utility of thistle shoot density versus standing forage biomass for predicting forage yield loss. This information could eventually be used to develop a simple and reliable method for producers to estimate forage losses in the field.

3.2 Materials and Methods

3.2.1 Study Sites

This research was carried out from 1999 to 2001 at 8 pastures situated throughout the Aspen Parkland of central Alberta (Table 3.1; Appendix 1.1). Within a site, selected pastures met the following criteria: (1) both physical conditions (e.g., soils and disturbance history) and forage sward composition were relatively uniform, (2) they had an abundant infestation of Canada thistle, and (3) they had not been sprayed for at least 3 years prior to 1999. With the exception of Sites 5 and 7, which contained perennial sow-thistle (*Sonchus arvensis* L.), all sites were relatively free of other noxious weeds. At

each site, a yield loss assessment was conducted on a 25 by 25 m area. Fences were built to exclude livestock, and soil samples collected in May 1999 to provide information on physical site characteristics (Table 3.1). All sites were tame pastures dominated by some combination of the following grasses: smooth brome (*Bromus inermis* Leyss.), Kentucky bluegrass (*Poa pratensis* L.), and quackgrass (*Agropyron repens* (L.) Beauv.) (Table 3.2).

Growing season precipitation data were collected for the three years of the study (Table 3.3). At most sites for all three years, total May to August rainfall was below local, 30-year averages, but ranged from 29% below to 24% above average. In 2001, precipitation in May, June, and most of July was lower at most sites compared to 1999 and 2000, despite the fact that two sites had above-average total precipitation from May-August. The majority of precipitation received in 2001 was in the form of thunderstorms that occurred at the end of the growing season (i.e., late July and early August).

3.2.2 Field Sampling

O'Sullivan et al. (1982, 1985) utilized thistle patches and their tendency to systematically spread radially to investigate thistle impacts on barley and canola yields. The authors measured crop yield in plots at seven sequential target levels of thistle shoot density from the outside to the inside of each patch, and calculated correlation coefficients between crop yield and thistle density. This method requires uniform patches with consistent gradients in thistle abundance. However, thistle patches at the 8 pastures investigated in the present study were often non-uniform in shape and density, making target levels of shoot density difficult to obtain. This characteristic was noted in other pastures in the region as well, and is likely due to differences in thistle

establishment and propagation in heterogeneous permanent pastures compared to annually cultivated and homogenized fields. Therefore, a modified approach was used that differed from O'Sullivan et al. (1982), but still captured a wide range of variation in thistle density and biomass. At each pasture site, 25 permanent 0.5 by 0.5 m (0.25 m^2) quadrats, spaced 5m apart, were established in a systematic, grid layout of 5 transects with 5 quadrats each. This pattern captured a wide distribution of thistle abundance among sampled quadrats at each location.

At peak standing biomass in August 1999, current annual herbage biomass (separated into grass and forb) was sampled to ground level in each quadrat, along with the following indicators of Canada thistle abundance: number of shoots (quadrat thistle density) and shoot dry weight ($kg \cdot ha^{-1}$). All harvested samples were oven-dried at 60°C to constant mass, and weighed. In addition to measuring thistle density in each 0.25 m^2 quadrat, the number of thistle shoots in a larger, 1 m^2 quadrat nested over the smaller area was also determined. This was done because of the high potential for above- and below-ground (i.e., root) competition effects on forage yield from adjacent thistle stems, and the patchy nature of thistles within most stands. At Sites 5 and 7, sow-thistle density and shoot dry weight were also sampled, as forage yield would have been affected by the presence of this species as well.

Throughout the summer of 2000, all Canada thistle plants were controlled using repeated applications of the systemic, broad-leaf herbicide clopyralid (3,6-dichloro-2-pyridinecarboxylic acid), at 0.6% concentration. Thistles were eliminated in an attempt to validate the initial yield loss relationships. That is, following thistle control, a significant increase in forage yield was expected, with larger increases in plots initially

containing more thistle. On plots containing <5% non-thistle forb biomass (i.e. Sites 1,2,3 and 6), herbicide applications were broadcast sprayed, while spot applications were applied only to thistle plants in plots containing >5% forb biomass (i.e. Sites 4,5,7 and 8). Spot applications were needed to minimize the removal of forbs other than thistle, which would have impacted the yield loss results. Where present, sow-thistle plants at Sites 5 and 7 were also controlled. During peak vegetation growth in August 2000, herbage was again sampled using the same procedure as the previous year at all sites except Site 6, where cattle broke into and grazed the plot, removing it from the 2000 analysis. In 2001, Site 6 was again sampled and included in the analysis for that year.

In the spring of 2001, few Canada thistle plants emerged in and around the quadrats at the various sites, but those that did were again sprayed. At peak vegetation growth in August, herbage was sampled at all sites except Site 3, which the landowner accidentally ploughed, removing it from the study.

In June of 1999, soil samples were collected at each site to provide base-line information on physical site characteristics. At eight randomly selected points within each yield loss assessment site, soil sub-samples were taken at both 0-15 and 15-30 cm depths. Sub-samples were pooled prior to lab analysis, with each depth analyzed separately. Results from lab analyses of the two soil depths were averaged for each site (Table 3.1). Nitrogen (nitrate), phosphorus (phosphate), and potassium analyses were conducted according to the methods of Ashworth and Mrazek (1995). Sulfur (sulfate), organic matter, pH, and electrical conductivity were determined using the methods of McKeague (1978). Soil texture was determined using hand texturing.

3.2.3 Analysis

To establish whether a relationship existed between forage yield and the various indicators of Canada thistle abundance, linear least squares regressions were carried out on the pre-validation data of 1999, as well as the validation data of 2000 and 2001. Initially, an attempt was made to fit the data to non-linear (i.e., logarithmic, as well as 2nd and 3rd order polynomial) models. Examination of the correlation coefficients and *P*-values revealed that non-linear equations generally resulted in no improvement in the fit of data points to the regression line, or in some cases a small (<5%) increase or decrease in the strength of correlations (data not shown). Therefore, it was decided to use the simplest model available that best described the data (i.e., simple linear regression). All data were tested for normality prior to analysis using the Shapiro-Wilks' statistic (SAS Institute Inc. 1988), and found to be normal ($P>0.10$).

A homogeneity test of the site-based regressions was initially conducted prior to analysis to determine whether sites could be pooled to develop an overall yield loss equation (data not shown). Several of the slopes and intercepts differed significantly ($P<0.05$), likely because of differences in soils and precipitation among sites (Tables 3.1 and 3.3). In addition, total herbage production, along with grass and forb composition, differed among sites (Table 3.2), and Sites 5 and 7 had a substantial amount of sow-thistle in addition to Canada thistle (i.e., 14% and 26% of total thistle biomass, respectively). As a result, the decision was made to analyze all 8 sites separately. Because some sites had a greater proportion of forbs than grasses, sites were analyzed either with total herbage yield (grass + forbs) or grass yield alone as the dependent variable. Total herbage yield was used if >5% of the herbage yield was made up of forbs,

and thistle had been spot sprayed, while grass yield was used if <5% of the herbage yield was made up of forbs and the thistle broadcast sprayed. Using this criterion, Sites 4, 5, 7, and 8 were analyzed using total herbage yield (Table 3.4), while Sites 1, 2, 3, and 6 were analyzed using grass yield (Table 3.5). Maximum forb yield among the latter sites in 1999 was 2%.

Empirical relationships were determined for forage yield as a function of increasing Canada thistle abundance (small and large quadrat shoot density, and small quadrat shoot biomass) according to the equation $Y = a + bX$, where Y = estimated forage yield in $kg \cdot ha^{-1}$ (dry weight), $a = Y$ intercept (estimated thistle-free forage yield), b = slope (index of competition; O'Sullivan et al. 1982), and X = the Canada thistle variable measured (Zar 1996). For 2000 and 2001, changes in herbage yield (ΔY) from 1999 to 2000, and from 1999 to 2001, respectively, were regressed against thistle removal (ΔX) in an attempt to validate the predicted yield loss relationship. Quadrats with greater initial thistle levels in 1999 were hypothesized to demonstrate greater increases in forage yield in 2000 and 2001 following thistle removal. All regressions were considered significant at $P<0.10$, unless noted otherwise. A less conservative significance value was used because of the large amount of variation that was present in the eight study pastures, which made correlations more difficult to detect.

3.3 Results and Discussion

3.3.1 Overall Yield Loss Trends

Although many of the correlations calculated between thistle and herbage parameters were non-significant ($P>0.10$), at all but 2 Sites (2 and 8), significant ($P<0.10$) relationships were detected. The pre-thistle removal data from 1999 had the greatest number of significant correlations (11), followed by the validation data of 2000 (9) and then 2001 (1; Table 3.6). All significant correlations from 1999 (n=11) were negative (Tables 3.4, 3.5), indicating greater amounts of thistle were consistently associated with reductions in forage. In contrast, the post-1999 significant correlations were largely positive (n=7/10), suggesting the removal of thistle often facilitated an increase in forage growth.

Although total rainfall for 2001 was nearly normal (Table 3.3), lack of moisture in May, June, and early July of that year likely contributed to the lower number of significant correlations found (data not shown). Low precipitation resulted in a delay of herbage growth in pastures across central Alberta. As a result, at the time of sampling in August 2001, grass and forb production were lower than in 1999 and 2000, thereby limiting the potential for the predicted increase in forage production that should have occurred with thistle removal. At some sites, total summer precipitation was similar among the three years of the study, but in these cases, the majority of precipitation came too late (e.g., late July / early August) to effect the same degree of pasture growth as the previous years (Table 3.3). As a result, the general strengthening of the validation relationships expected in 2001 simply did not occur.

The absence of any significant relationship between thistle and forage at 2 locations (Sites 2 and 8) highlights the variable impact of thistle on forage yield, and the difficulty associated with quantitatively detecting a yield loss effect. Sites with low precipitation (i.e., lower than the 30-year regional average, or lower than previous years of the study) after 1999, would likely have resulted in limited increases in non-thistle herbage following thistle removal than in years with greater precipitation, thereby preventing a detectable yield gain following thistle control. Moreover, sites with greater precipitation in 1999 are likely to decrease in production with normal rainfall in 2000 or 2001, regardless of changes in Canada thistle. In terms of soil differences, sites with less productive soils would have had less-pronounced yield responses, as soil nutrients would have limited the magnitude of forage response following thistle removal. At these sites, yield responses after thistle removal may have required longer than 2 years of monitoring to detect. Forage sward composition could also have affected the magnitude of yield loss and gain relationships. For example, sites dominated by more competitive, rhizomatous grass species such as smooth brome and quackgrass may have been initially more resistant to yield loss, but alternatively, responded relatively quickly to the removal of thistle compared to sites containing a greater proportion of less competitive herbage species. In addition, sites with greater thistle abundance among quadrats may have resulted in a more detectable yield loss effect, as thistle competition would have been more clearly expressed. A more varied initial level of thistle abundance may also have led to a more detectable yield loss effect, as a wider numerical range of forage response may have been possible.

3.3.2 Site Specific Responses

The general yield loss trend that was hypothesized for the 3 years of the experiment was best illustrated by the data from Site 1 (Table 3.5 and Fig. 3.1), which had the greatest initial thistle biomass levels (Table 3.2). The larger increase in grass yield in 2001 compared to 2000 can be attributed to the likelihood that some competition occurred between thistle plants and grass in 2000 before thistles were removed in early summer of that year. Similar forage changes were observed at Sites 3 (Table 3.5 and Fig. 3.2) and 4 (Table 3.4 and Fig. 3.3). Unfortunately, Site 3 was lost in 2001, precluding an assessment of yield response in the third year.

While simple linear regression best described the data from most locations, a logarithmic equation for Site 3 in 1999 resulted in a >5% increase in the correlation coefficient for the relationship between grass biomass and large plot thistle density [i.e., $Y = 4163 - 940 \ln(X)$, $r = -0.55$, $P=0.01$] compared to the linear equation (i.e., $r = -0.47$, Table 3.5). Additionally, for Site 1 in 2001, a logarithmic equation for the relationship between change in grass biomass and large plot thistle density removal [i.e., $\Delta Y = 1415 \ln(\Delta X) - 1332$, $r = -0.48$, $P=0.03$] resulted in a >5% increase in the correlation coefficient compared to the linear equation (i.e., $r = 0.39$; Table 3.5). While there appeared to be an upper limit to forage biomass in relation to thistle in these correlations, linear equations best described the vast majority of thistle-forage relationships. While forage biomass increase would, theoretically, reach an upper limit in response to thistle density or biomass removal, it is apparent that the current data set does not capture the range of data where this would occur (Tables 3.4, 3.5).

In general, forage response among sites was inconsistent, likely due to differences in precipitation, soils, and vegetation among study pastures. In 2001, only Site 1 had a significant ($P<0.10$), and Site 6, a nearly significant ($P<0.20$), yield gain (Table 3.5). Both these sites were considered to have had adequate moisture. However, drought stress at Sites 4, 7, and 8 in 2001 appeared to limit the response of herbage, thereby reducing the potential for yield gains. Despite this, the general trend among most sites was for increasing forage yield with greater thistle removal. Had monitoring continued past 2001, it is possible that the return of adequate precipitation would have led to even more significant yield gains.

In terms of soil properties, the high soil organic matter (O.M.) at Site 1 (33.5%) and favorable nutrient status for forage and thistle growth (130 kg·ha^{-1} N), likely contributed to the significant correlations at this site throughout 1999-2001 (Tables 3.1, 3.5). Because soil fertility would not have limited grass and thistle growth, competition effects between Canada thistle and grass may have been more pronounced, and yield loss effects easier to detect. In contrast, soil O.M. and fertility were lowest at Sites 4 and 8, which, when combined with the lower precipitation of 2001, likely contributed to the lack of significant yield gains in that year (Tables 3.1, 3.4).

A number of vegetation factors including initial thistle abundance, sow-thistle presence/absence, the inadvertent removal of forbs despite spot-spraying of thistles, and forage sward production and vigor, may also have influenced forage yield response. Sites with greater initial thistle abundance and forage biomass, such as Sites 1 and 6 (Table 3.2), would have had greater potential for yield loss effects, as competition would have been enhanced compared to sites with lower initial thistle abundance. For example,

thistle plants at Site 2 were generally small, as illustrated by the relatively low initial thistle biomass (784 kg·ha^{-1}) and high thistle density (33 shoots·m^{-1}; Table 3.2). Consequently, competition at the individual plant level may not have been great, thereby preventing the detection of a significant yield loss effect at Site 2 in 1999, as well as subsequent yield gains following thistle removal. At Site 7, the low initial biomass of both Canada and sow-thistle likely dampened the potential for a marked yield gain with thistle removal. In addition, because of the abundant forb component (33% of total herbage production; Table 3.2) and the fact that forbs (mainly alfalfa and sweet clover) were growing in close proximity to thistle, spot-spraying probably resulted in the unplanned removal of many forbs. In these situations, any yield gain would have had to first compensate for the removal of non-target forbs, thereby accounting for the weakly expressed positive yield response at Site 7. Similarly, the lack of significant yield gain at Sites 5 and 8, where forbs made up 9 and 7% of total herbage production, respectively, were likely due, at least in part, to the inadvertent removal of forbs by herbicide (mostly dandelion at both sites, Table 3.2).

Site 5 also had several negative correlations during validation in 2000 and 2001 (Table 3.4), indicating the removed forbs were not replaced by an associated increase in grass growth in the short term (2000 and 2001). This finding may be because of the low vigor of the forage stand, which was reflected in its low, initial grass production (Table 3.2). There was, however, a turn-around at Site 5 in 2001 to a positive, albeit non-significant, increase in forage yield in 2001. The grass sward at Site 4 was also sparse and forage vigor low (Table 3.2). It is possible that with adequate precipitation and forage sward recovery, there would eventually be sufficient increases in herbage

production at these sites to effect significant yield gains. These results underscore the importance of time-delays in forage yield response, and further highlight the site-specific nature of yield loss assessments in pasture environments.

Overall, the strengths of the yield loss relationships in the present study were lower than that reported by O'Sullivan et al. (1982, 1985) and Moyer et al. (1991) in Alberta. There also appeared to be more variation in our data, as illustrated by the relatively large standard errors (Tables 3.4 and 3.5). This variation was likely due to heterogeneity in soils, precipitation, and forage sward composition among and within sites, and is the most probable reason for the relatively inconsistent correlations.

The studies of barley and canola yield losses by O'Sullivan et al. (1982, 1985) found stronger correlations between Canada thistle and crop loss (e.g., r = -0.55 to -0.81), but were carried out under different conditions than the present study. Plots used in those studies were located in cultivated, homogeneous, black loam soils, with uniform, seeded crop populations. In the case of Moyer et al. (1991), irrigated alfalfa seed fields were studied, which were likely more uniform in soils and vegetation than the pasture sites of the present study, and were not affected by moisture stress. Our results suggest quantifying yield losses due to Canada thistle in permanent pasture is more difficult. Permanent pastures are inherently variable; they usually contain rodent disturbances such as molehills and ground squirrel disturbances, have patches of higher soil N as a result of livestock nutrient redistribution, have non-uniform populations of Canada thistle, and are generally more variable in vegetation composition. Consequently, representative study pastures inevitably have a high degree of variation in soils, forage sward composition, and moisture regime, leading to varied yield responses.

3.3.3 Comparison of Thistle Variables

Crop yield losses are often related to weed density only (e.g., O'Sullivan et al. 1985; McLennan et al. 1991). However, Hume (1985) found that annual weed shoot dry weight ($g \cdot m^{-2}$) estimated relative spring wheat yield better than annual weed density. In contrast, O'Sullivan et al. (1982) and Donald and Khan (1992) found no difference between Canada thistle density and shoot dry matter yield ($g \cdot m^{-2}$) for predicting barley and spring wheat yields, respectively.

In the current investigation, small and large plot thistle densities were compared with each other and with thistle biomass to evaluate whether these indicators of thistle abundance differed in their ability to assess forage yield losses. Tests were conducted to determine whether the dependent variable (forage biomass) varied in its response to interactions between every combination of the three independent, predictor variables (small and large plot thistle density, and thistle biomass). Interactions that were significant ($P<0.10$) indicated that the two thistle variables tested differed in their ability to predict forage biomass (Zar 1996). Comparisons among the three thistle variables for the 1999 data showed that small and large plot thistle density differed from each other, but not from thistle biomass, in their ability to predict forage yield loss ($P<0.10$). Additionally, there were no statistical differences among the three thistle variables for the validation data of 2000 and 2001.

Differences between small and large plot thistle density in 1999 may have been the result of site differences, as Sites 1, 4, 5, and 7 had significant regressions for small plot thistle density, while Sites 1, 3, 4, and 6 had significant regressions for large plot

thistle density (Tables 3.4, 3.5). Sites 4, 5, and 7 had >5% forbs, while 1, 3, and 6 had <2% forbs, suggesting that larger-quadrat thistle density may have been a better predictor of forage yield loss when the forage sward was dominated by grass. Grass swards may be more susceptible to root competition effects from nearby thistle plants (i.e., those outside the small quadrat but inside the larger one) than mixed swards. Dandelion and alfalfa were common forbs in the present study, and because both are perennials with deep taproots, it is possible that they experienced less direct competition with these adjacent thistles, thereby minimizing their effects. In contrast, fibrous rooted grasses may be more susceptible to direct root competition with nearby thistle.

The relative utility of the three thistle variables for predicting forage yield loss was evaluated by tallying the number of sites with significant correlations and determining which variable had the most significant correlations (Table 3.6). In 1999, small and large plot thistle density appeared to be marginally better at predicting forage yield loss than thistle biomass, while in 2000, change in thistle biomass appeared to be the best predictor. In 2001, all variables were generally poor predictors. Because large plot thistle density had the greatest overall number of significant correlations (Table 3.6), counting thistle shoots in larger quadrats may be preferred over using smaller quadrats or clipping shoots to predict forage yield loss. These results also suggest that competition effects on forages from adjacent thistle extends out some distance beyond the immediate vicinity of the forage plants, and may be below-ground in nature.

Although there was little difference in the number of significant correlations among the three thistle variables, some inferences can be made relating to the utility of these characteristics at different pasture sites. For example, all three thistle variables

could have been successfully used to predict forage yield loss at Sites 1 and 4 in 1999, and forage yield gain following thistle removal at Site 3 in 2000 (Tables 3.4, 3.5). In addition, yield gain could be predicted by large plot thistle density and biomass values at Site 1 in 2000. Although soils and vegetation composition (including initial forb and thistle abundance) differed greatly among these sites (Tables 3.1, 3.2), all four sites (1, 3, 4 and 5) had ample rainfall in the years when significant yield losses were found. When lower than average moisture was received in 2001 at Sites 4 and 5, none of the thistle variables were able to predict forage yield gain following thistle removal. These results suggest that growing conditions in a given year may be more important than the type of thistle variable used in predicting forage yield loss. That is, in years with adequate moisture, either thistle density or biomass may adequately predict yield loss, while in drier years, it may not be possible to predict forage yield loss with any thistle variable.

From a producer's perspective, thistle density would be more useful than thistle biomass for predicting yield loss. Thistle density could be determined more quickly and easily than clipping thistle shoots, and based on a simple equation, forage yield loss estimated. Based on the predicted loss, management decisions could then be made to assess the economics of various control options.

However, thistle shoot biomass may still be a better predictor of forage yield loss than thistle density. Thistle shoot density does not take into account differences in the size of individual thistle plants, which might make it a less accurate estimator of thistle abundance than biomass. For example, there is wide variation in the height and weight of thistle shoots under field conditions, which can result in situations where on a per area basis, many small, spindly thistles may provide relatively ineffectual competition, while a

few large, leafy thistles with larger root systems would likely provide much more competition through increased shading and more effective exploitation of moisture and soil nutrients. As a result, thistle shoot density may not accurately reflect the level of competition. Both Schreiber (1967) and Moyer et al. (1991) looked at only Canada thistle density in their studies of alfalfa yield loss. To our knowledge, this study is the first attempt to determine whether thistle density and biomass vary in their ability to predict forage yield loss. Although our results suggest they do not differ substantially, further studies are needed, as the wide variation in the present data may obscure real differences (e.g., Tables 3.4 and 3.5).

3.4 Conclusions and Management Recommendations

Knowledge of pasture forage yield loss could help encourage livestock producers to actively manage weeds. No information currently exists on the effects of Canada thistle on forage production in central Alberta pastures. This study attempted to address this lack of information by examining thistle impacts on pasture forage yields.

Differences among study sites related to precipitation, soils, forage species composition, and initial thistle levels, resulted in variable yield losses. Although every attempt was made to choose pastures internally uniform in soils and vegetation composition, it was impossible to find perfectly homogeneous study sites. Permanent pastures have features that include molehills and ground squirrel mounds, patches of greater nutrient accumulation, and variable distribution and abundance of plant species, which make them more of a heterogeneous mosaic rather than a uniform, homogeneous

medium for experimental research. Although representative of pastures across central Alberta, this high variation within and among study sites led to inconsistent and site-specific yield loss effects. In addition, differences in time-delays of yield response among sites were likely linked to a number of factors, including below-average precipitation, low soil nutrient status, and low vigor and production of the forage sward.

Because of the site-specific nature of yield loss assessments in pastures, it appears impossible to combine data from multiple sites to arrive at a single, universal yield loss assessment. For a producer, this complicates the practicality of assessing forage yield loss in thistle-infested pastures. Because of the heterogeneity and variation inherent to pastures, yield loss assessments undertaken must take into account individual site conditions, including soils (nutrients and disturbance history), forage composition and productivity, as well as moisture regime. In years with adequate precipitation, more productive pastures with increased thistle abundance may have a greater tendency for yield losses in the short term, while yield reductions in less productive pastures may be less pronounced, difficult to detect, and less likely to lead to detectable yield gains with thistle control.

Given that thistle shoot density and standing biomass differed little in their ability to predict forage yield loss, either could be used by a producer to estimate yield loss. Thistle biomass should, theoretically, give a more accurate indication of thistle abundance, but in terms of practicality, thistle density would be preferred, as it can be assessed more easily. Our data also suggest that either small (0.25 m^2) or large (1 m^2) quadrats could be used in a yield loss assessment, although the latter may be better in grass dominated swards.

In spite of large variability in the data from the 8 pastures studied, the yield loss relationships validated at Sites 1 and 3 demonstrated thistle densities of 20 shoots·m^{-2} can result in forage yield reductions of 510 and 868 kg·ha^{-1}, respectively (1999 large plot thistle density relationship, Table 3.5). As a percentage of thistle-free yield, these losses are within the range of documented yield losses caused by Canada thistle in annual crops and irrigated alfalfa seed fields in Alberta (O'Sullivan et al. 1982; 1985; Moyer et al. 1991).

Further research is needed to determine how precipitation and site-based factors such as soil type and nutrients, and species composition affect forage yield loss caused by Canada thistle. Future directions in Canada thistle research should include an examination of not only above-ground competition effects, but also below-ground or root to root interactions. For example, above-ground foliage of thistles and adjacent desirable forage plants could be physically separated in a greenhouse or controlled field setting to enable root competition effects to be measured.

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Table 3.1 Physical site (i.e., soil) characteristics of the eight yield loss assessment sites, as sampled in May 1999[z].

Site	Location / Lat.-Lon.[y]	Texture / Soil Type	Slope / Aspect	Nutrients ($kg \cdot ha^{-1}$)				pH	EC (dS/ cm)	OM (%)
				N	P	K	S			
1	Barrhead 54° 00' 57" N 114° 22' 44" W	Loam, Orthic Humic Gleysol	Level / NA	130	11	1009	3289	6.7	2.9	33.5
2	Chipman 53° 42' 24" N 112° 33' 10" W	Loam, Orthic Black Chernozem	Level / NA	47	7	428	33	6.9	0.5	10.1
3	Ellerslie 53° 25' 08" N 113° 23' 35" W	Silt Loam, Orthic Black Chernozem	Level / NA	28	262	1710	78	6.3	0.43	9.6
4	St. Michael 53° 50' 14" N 112° 38' 52" W	Silty Clay Loam, Black Solodized Solonetz	Gentle slope / North-east	12	113	570	11	7.1	0.60	4.3
5	Lamont 53° 45' 29" N 112° 40' 45" W	Silty Clay Loam, Orthic Black Chernozem	Level / NA	58	341	1558	59	7.3	0.95	11.9
6	Mayerthorpe 53° 56' 13" N 114° 58' 50" W	Silt Loam, Orthic Humic Gleysol	Level / NA	231	1083	4585	175	6.5	1.15	25.5
7	Two Hills 53° 47' 5" N 111° 27' 24" W	Silt Loam, Gleyed Dark Gray Chernozem	Gentle slope / North	188	26	1000	20	6.6	0.82	9.3
8	Cooking Lake 53° 28' 32" N 112° 58' 41" W	Silty Clay Loam, Dark Gray Chernozem	Gentle slope / south	12	137	778	54	6.8	1.03	5.2

[z]All values represent the average of the two soil depths that were sampled and analyzed separately (0-15 and 15-30 cm). Nitrogen, phosphorus, and sulfur were present in the form of nitrate, phosphate, and sulfate, respectively.

[y]Location is the name of the town nearest the study site, while Lat.-Lon. are the exact coordinates of the site.

Table 3.2 Vegetation characteristics of the eight yield loss assessment sites, as sampled in August 1999.

Site	Dominant Grass Species	Dominant Forb Species	Average Herbage production ($kg \cdot ha^{-1}$)[z] (% Grass, % Forbs)	Average Thistle Biomass ($kg \cdot ha^{-1}$)[y]	Average Thistle Density (no. shoots $\cdot m^{-2}$)[y]
1	Quackgrass (*Agropyron repens* (L.) Beauv.), Kentucky bluegrass (*Poa pratensis* L.), Meadow brome (*Bromus biebersteinii* Roem. & Schult.)	Dandelion (*Taraxacum officinale* Web.)	4635 ± 194 (98, 2)	2986 ± 553 (193 – 10 577)	46 ± 5 (9 – 89)
2	Smooth brome (*Bromus inermis* Leyss.), Kentucky bluegrass	Dandelion, Common Yarrow (*Achillea millefolium* L.)	1963 ± 109 (99, 1)	784 ± 89 (168 – 1696)	33 ± 2 (17 – 50)
3	Kentucky bluegrass	Dandelion	1360 ± 133 (100, 0)	690 ± 79 (148 – 1540)	21 ± 1 (8 – 35)
4	Kentucky bluegrass	Common Yarrow, Bedstraw (*Galium* spp. L.)	1002 ± 49 (88, 12)	1198 ± 134 (0 – 2702)	25 ± 2 (4 – 42)
5	Smooth brome, Kentucky bluegrass	Dandelion	1502 ± 82 (91, 9)	480 ± 90 (0 – 1648)	32 ± 5 (0 – 92)
6	Smooth brome, Kentucky bluegrass	Dandelion	2499 ± 147 (99, 1)	2871 ± 551 (71 – 12 694)	53 ± 4 (15 – 86)
7	Smooth brome, Kentucky bluegrass	Alfalfa (*Medicago sativa* L.), Sweetclover (*Melilotus* spp. L.)	2747 ± 134 (67, 33)	311 ± 37 (30 - 719)	57 ± 7 (12 – 148)
8	Smooth brome, Kentucky bluegrass	Dandelion, Alfalfa	2465 ± 95 (93, 7)	952 ± 161 (8 – 3272)	19 ± 2 (6 – 33)

[z]Means ± standard error. Proportions (i.e., mean percentages) of total herbage production made up of grass and non-thistle forbs are in parentheses.

[y]Means ± standard error. Values in parentheses represent the range of the data. Thistle biomass and density at Sites 5 and 7 includes perennial sow-thistle, in addition to Canada thistle. Perennial sow-thistle density (no. shoots $\cdot m^{-2}$) and biomass ($kg \cdot ha^{-1}$) for site 5 was 10 ± 3 and 70 ± 30, and for site 7 was 26 ± 7 and 82 ± 27, respectively. Perennial sow-thistle biomass at sites 5 and 7 made up 15 and 26% of total thistle biomass, respectively.

Table 3.3 Growing season (May 1-August 31) precipitation for the 8 yield loss sites for 1999, 2000, and 2001, as well as the regional 30-year averages.

Sites	Precipitation (mm)			
	1999	2000	2001	30-yr average
1, 6	281	301	292	319
2, 4, 5	235	272	279	263
3,8	297	304	310	318
7	194	248	219	251

Table 3.4 Relationships between total herbage yield (kg·ha^{-1}) and three predictors (i.e., indicators of Canada thistle abundance) over three years at 4 sites in central Alberta. Changes in yield (ΔY) represent the change in yield from 1999 to 2000, and from 1999 to 2001, after thistle removal (ΔX) in 2000.

Predictor (X)	Year (s)	Site	Functional Relationship[z]	r[y]	P ≥ F[x]
Small Plot Thistle Density (no. shoots per 0.25 m^2)	1999	4	$Y = 1236 (\pm 95) - 33.1 (\pm 12.0) X$	−0.50	** (0.01)
		5	$Y = 1701 (\pm 136) - 24.6 (\pm 13.7) X$	−0.35	* (0.09)
		7	$Y = 3173 (\pm 246) - 30.0 (\pm 14.9) X$	−0.39	* (0.06)
		8	$Y = 2434 (\pm 222) + 5.2 (\pm 34.0) X$	0.03	NS (0.88)
	1999-2000	4	$\Delta Y = -34.3 (\pm 138) + 28.4 (\pm 17.4) \Delta X$	0.32	NS (0.12)
		5	$\Delta Y = 665 (\pm 133) - 27.0 (\pm 13.4) \Delta X$	−0.39	* (0.06)
		7	$\Delta Y = -600 (\pm 228) + 15.0 (\pm 13.8) \Delta X$	0.22	NS (0.29)
		8	$\Delta Y = -341 (\pm 276) - 7.1 (\pm 42.2) \Delta X$	−0.03	NS (0.87)
	1999-2001	4	$\Delta Y = 348 (\pm 202) + 22.3 (\pm 25.4) \Delta X$	0.18	NS (0.39)
		5	$\Delta Y = 1100 (\pm 322) + 19.8 (\pm 32.5) \Delta X$	0.13	NS (0.55)
		7	$\Delta Y = 256 (\pm 409) + 6.5 (\pm 24.7) \Delta X$	0.05	NS (0.80)
		8	$\Delta Y = 588 (\pm 365) + 50.4 (\pm 55.8) \Delta X$	0.19	NS (0.38)
Large Plot Thistle Density (no. shoots per 1m^2)	1999	4	$Y = 1289 (\pm 145) - 11.4 (\pm 5.4) X$	−0.40	** (0.04)
		5	$Y = 1519 (\pm 218) - 0.8 (\pm 9.9) X$	−0.02	NS (0.94)
		7	$Y = 3370 (\pm 448) - 19.2 (\pm 13.1) X$	−0.29	NS (0.16)
		8	$Y = 2435 (\pm 253) + 1.5 (\pm 12.2) X$	0.03	NS (0.90)
	1999-2000	4	$\Delta Y = -89 (\pm 202) + 10.1 (\pm 7.6) \Delta X$	0.27	NS (0.20)
		5	$\Delta Y = 877 (\pm 192) - 21.2 (\pm 8.7) \Delta X$	−0.45	** (0.02)
		7	$\Delta Y = -668 (\pm 406) + 8.6 (\pm 12.0) \Delta X$	0.15	NS (0.48)
		8	$\Delta Y = -361 (\pm 314) - 1.1 (\pm 15.1) \Delta X$	−0.01	NS (0.94)
	1999-2001	4	$\Delta Y = 339 (\pm 292) + 6.6 (\pm 11.0) \Delta X$	0.12	NS (0.56)
		5	$\Delta Y = 1349 (\pm 486) - 4.3 (\pm 22.1) \Delta X$	−0.04	NS (0.85)
		7	$\Delta Y = -64 (\pm 713) + 12.7 (\pm 21.0) \Delta X$	0.12	NS (0.55)
		8	$\Delta Y = 512 (\pm 414) + 19.4 (\pm 19.9) \Delta X$	0.20	NS (0.34)
Thistle Biomass (g per 0.25 m^2)	1999	4	$Y = 1193 (\pm 94) - 6.4 (\pm 2.8) X$	−0.43	** (0.03)
		5	$Y = 1593 (\pm 121) - 7.5 (\pm 7.4) X$	−0.21	NS (0.32)
		7	$Y = 3359 (\pm 226) - 78.7 (\pm 25.0) X$	−0.55	*** (0.005)
		8	$Y = 2509 (\pm 152) - 1.8 (\pm 4.9) X$	−0.08	NS (0.71)
	1999-2000	4	$\Delta Y = -50 (\pm 128) + 7.3 (\pm 3.8) \Delta X$	0.37	* (0.07)
		5	$\Delta Y = 624 (\pm 112) - 14.8 (\pm 6.9) \Delta X$	−0.41	** (0.04)
		7	$\Delta Y = -643 (\pm 229) + 32.9 (\pm 25.3) \Delta X$	0.26	NS (0.21)
		8	$\Delta Y = -411 (\pm 190) + 1.2 (\pm 6.1) \Delta X$	0.04	NS (0.85)
	1999-2001	4	$\Delta Y = 267 (\pm 186) + 8.0 (\pm 5.4) \Delta X$	0.29	NS (0.16)
		5	$\Delta Y = 1047 (\pm 271) + 17.8 (\pm 16.6) \Delta X$	0.22	NS (0.30)
		7	$\Delta Y = 22 (\pm 407) + 41.9 (\pm 45.1) \Delta X$	0.19	NS (0.36)
		8	$\Delta Y = 797 (\pm 254) + 3.6 (\pm 8.2) \Delta X$	0.09	NS (0.66)

[z]Means (± standard error) are presented for equation intercepts (a) and slope (b).
[y]Correlation coefficient.
[x]Correlations were either not significant (NS) or significantly different at $P < 0.10$ (*), $P < 0.05$ (**), or $P < 0.01$ (***). Values in parentheses are the actual P values.

Table 3.5 Relationships between grass yield ($kg \cdot ha^{-1}$) and three predictors (i.e., indicators of Canada thistle abundance) over three years at 4 sites in central Alberta. Changes in yield (ΔY) represent the change in yield from 1999 to 2000, and from 1999 to 2001, after thistle removal (ΔX) in 2000.

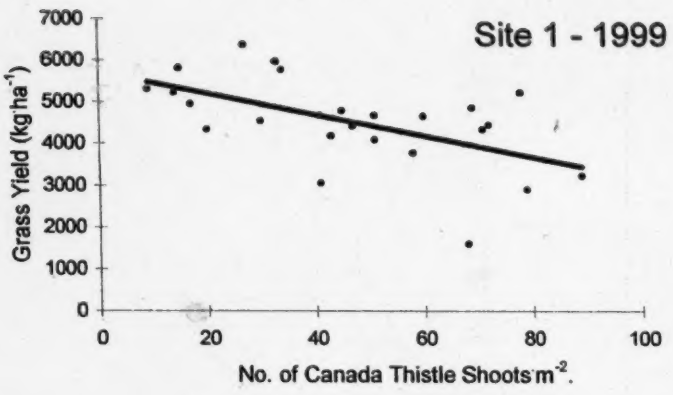
Predictor (X)	Year (s)	Site	Functional Relationship[z]	r[y]	$P \geq F$[x]
Small Plot Thistle Density (no. shoots per 0.25 m^2)	1999	1	$Y = 5294 (\pm 319) - 61.3 (\pm 20.8) X$	−0.52	*** (0.007)
		2	$Y = 2062 (\pm 293) - 13.1 (\pm 29.7) X$	−0.09	NS (0.66)
		3	$Y = 1629 (\pm 522) - 39.4 (\pm 73.7) X$	−0.11	NS (0.60)
		6	$Y = 2664 (\pm 325) - 13.4 (\pm 20.0) X$	−0.14	NS (0.51)
	1999-2000	1	$\Delta Y = 788 (\pm 410) + 41.6 (\pm 26.7) \Delta X$	0.31	NS (0.13)
		2	$\Delta Y = 1321 (\pm 323) - 34.0 (\pm 32.8) \Delta X$	−0.21	NS (0.31)
		3	$\Delta Y = 13 (\pm 435) + 102.6 (\pm 61.5) \Delta X$	0.33	* (0.10)
	1999-2001	1	$\Delta Y = 3292 (\pm 630) + 47.2 (\pm 41.0) \Delta X$	0.23	NS (0.26)
		2	$\Delta Y = 2222 (\pm 699) - 43.0 (\pm 71.0) \Delta X$	−0.13	NS (0.55)
		6	$\Delta Y = 1661 (\pm 599) + 49.5 (\pm 36.9) \Delta X$	0.27	NS (0.19)
Large Plot Thistle Density (no. shoots per 1 m^2)	1999	1	$Y = 5710 (\pm 415) - 25.5 (\pm 8.0) X$	−0.55	*** (0.004)
		2	$Y = 2544 (\pm 465) - 18.2 (\pm 13.7) X$	−0.27	NS (0.20)
		3	$Y = 2272 (\pm 374) - 43.4 (\pm 16.8) X$	−0.47	** (0.02)
		6	$Y = 3134 (\pm 395) - 12.4 (\pm 6.9) X$	−0.35	* (0.09)
	1999-2000	1	$\Delta Y = 321 (\pm 524) + 21.3 (\pm 10.2) \Delta X$	0.40	** (0.04)
		2	$\Delta Y = 1272 (\pm 540) - 7.9 (\pm 15.9) \Delta X$	−0.10	NS (0.63)
		3	$\Delta Y = 36 (\pm 341) + 32.3 (\pm 15.4) \Delta X$	0.40	** (0.04)
	1999-2001	1	$\Delta Y = 2429 (\pm 791) + 31.3 (\pm 15.3) \Delta X$	0.39	* (0.05)
		2	$\Delta Y = 2099 (\pm 1156) - 8.1 (\pm 34.1) \Delta X$	−0.05	NS (0.82)
		6	$\Delta Y = 1356 (\pm 768) + 19.0 (\pm 13.4) \Delta X$	0.28	NS (0.17)
Thistle Biomass (g per 0.25 m^{-2})	1999	1	$Y = 5165 (\pm 266) - 8.6 (\pm 2.6) X$	−0.56	*** (0.004)
		2	$Y = 1840 (\pm 233) + 5.3 (\pm 10.4) X$	0.11	NS (0.62)
		3	$Y = 1164 (\pm 272) + 11.3 (\pm 13.8) X$	0.17	NS (0.42)
		6	$Y = 2521 (\pm 224) - 0.7 (\pm 2.3) X$	−0.06	NS (0.76)
	1999-2000	1	$\Delta Y = 857 (\pm 346) + 6.1 (\pm 3.4) \Delta X$	0.35	* (0.09)
		2	$\Delta Y = 847 (\pm 260) + 8.5 (\pm 11.6) \Delta X$	0.15	NS (0.47)
		3	$\Delta Y = 275 (\pm 218) + 25.5 (\pm 11.0) \Delta X$	0.43	** (0.03)
	1999-2001	1	$\Delta Y = 3493 (\pm 544) + 5.3 (\pm 5.4) \Delta X$	0.20	NS (0.34)
		2	$\Delta Y = 1851 (\pm 562) - 1.0 (\pm 25.0) \Delta X$	−0.01	NS (0.97)
		6	$\Delta Y = 1962 (\pm 409) + 5.7 (\pm 4.2) \Delta X$	0.28	NS (0.18)

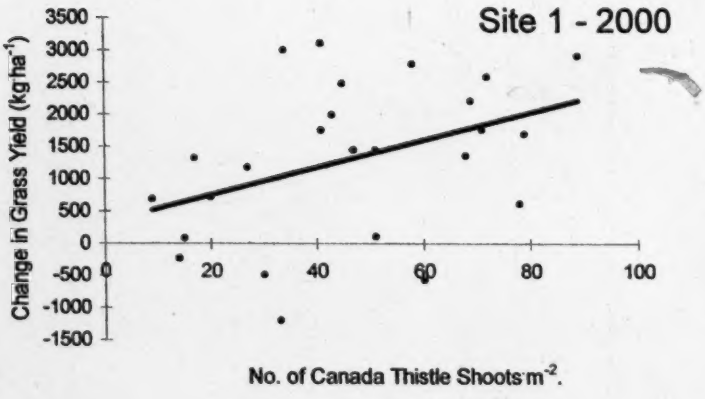
[z]Means (± standard error) are presented for equation intercepts (a) and slope (b).
[y]Correlation coefficient.
[x]Correlations were either not significant (NS) or significantly different at $P < 0.10$ (*), $P < 0.05$ (**), or $P < 0.01$ (***). Values in parentheses are the actual P values.

Table 3.6 A comparison of the number of significant correlations between the three thistle variables and forage parameters measured in 1999, 2000, and 2001.

Predictor (X)	Number of Significant Correlations[z]			Total
	1999	2000	2001	
Small Plot Thistle Density (no. shoots per 0.25 m^2)	4 / 8	2 / 8	0 / 8	6
Large Plot Thistle Density (no. shoots per 1m^2)	4 / 8	3 / 8	1 / 8	8
Thistle Biomass (g per 0.25 m^{-2})	3 / 8	4 / 8	0 / 8	7
Total	11	9	1	21

[z]Significant correlations (out of 8 possible comparisons; $P < 0.10$) were totaled, regardless of whether total herbage or grass yield were used as dependent variables.





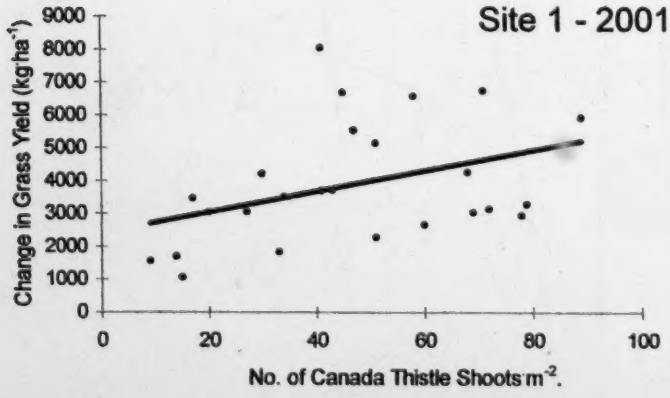
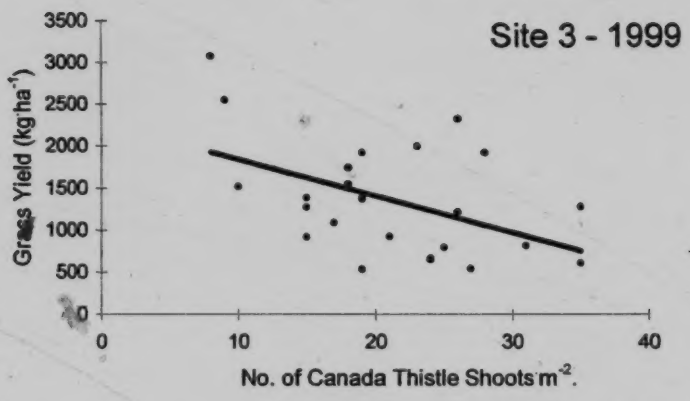


Figure 3.1 Relationship between grass yield ($kg \cdot ha^{-1}$) and large plot Canada thistle density ($shoots \cdot m^{-2}$) for Site 1 in 1999, 2000, and 2001. The regression equation for 1999 was: $Y = 5710 - 25.5X$, $r^2 = 0.30$, $P < 0.01$. Following thistle removal, the following equations were developed from the 2000 and 2001 data, respectively: $\Delta Y = 321 + 21.3\Delta X$, $r^2 = 0.16$, $P < 0.05$ and $\Delta Y = 2429 + 31.3\Delta X$, $r^2 = 0.15$, $P = 0.05$. Y = grass yield; X = number Canada thistle $shoots \cdot m^{-2}$; ΔY = change in grass yield from 1999 to 2000, or 1999 to 2001; ΔX = number of Canada thistle $shoots \cdot m^{-2}$ removed in 2000.



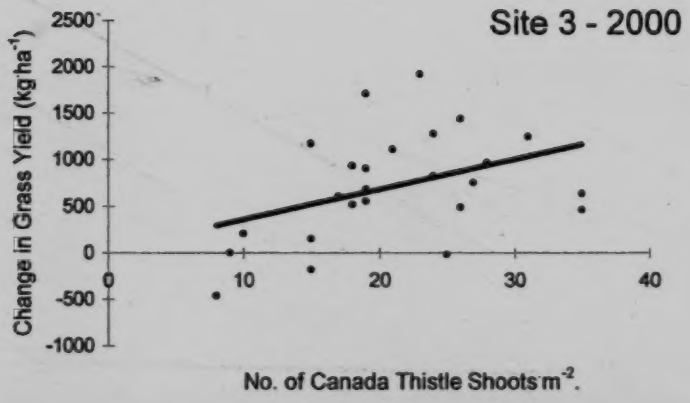


Figure 3.2 Relationship between grass yield ($kg \cdot ha^{-1}$) and large plot Canada thistle density ($shoots \cdot m^{-2}$) for Site 3 in 1999 and 2000. The regression equation for 1999 was: $Y = 2272 - 43.4X$, $r^2 = 0.22$, $P < 0.05$. Following thistle removal, the following equation was developed from the 2000 data: $\Delta Y = 36 + 32.3\Delta X$, $r^2 = 0.16$, $P < 0.05$. Y = grass yield; X = number Canada thistle shoots m^{-2}; ΔY = change in grass yield from 1999 to 2000; ΔX = number of Canada thistle $shoots \cdot m^{-2}$ removed in 2000.

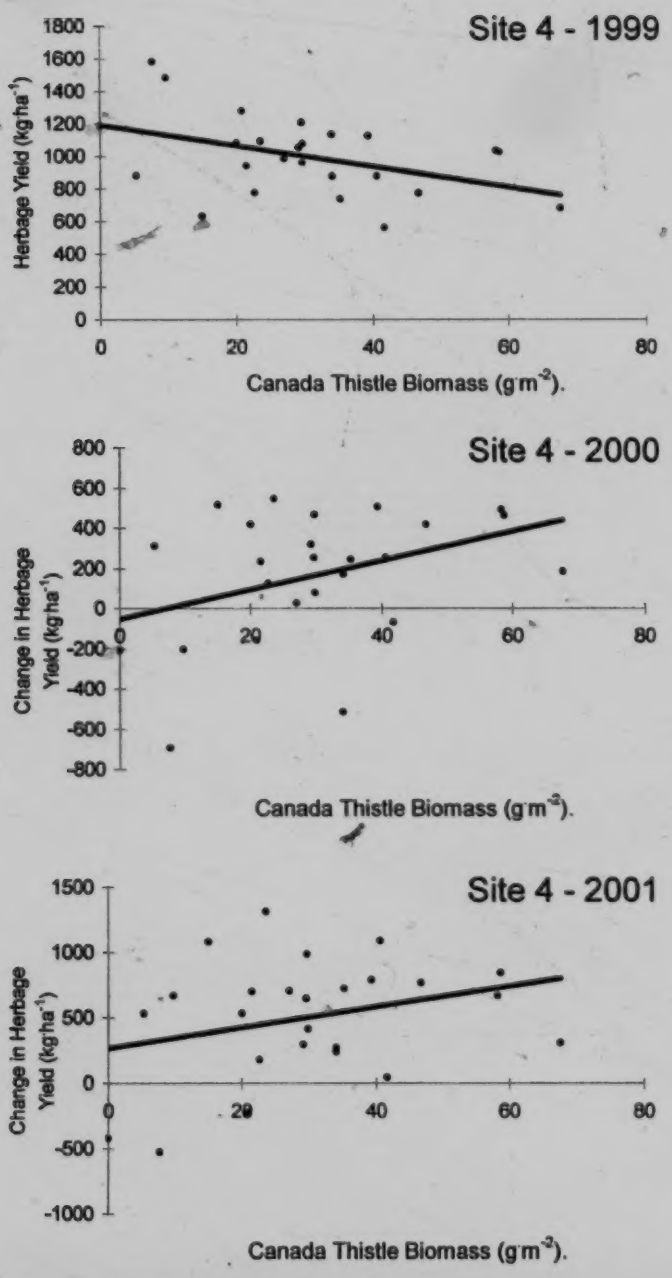


Figure 3.3 Relationship between herbage yield (kg·ha^{-1}) and Canada thistle yield (g/0.25 m^2) for Site 4 in 1999, 2000, and 2001. The regression equation for 1999 was: $Y = 1193 - 6.4X$, $r^2 = 0.18$, $P < 0.05$. Following thistle removal, the following equations were developed from the 2000 and 2001 data, respectively: $\Delta Y = -50 + 7.3\Delta X$, $r^2 = 0.14$, $P = 0.07$ and $\Delta Y = 267 + 8.0\Delta X$, $r^2 = 0.08$, $P = 0.16$. Y = total herbage yield; X = number Canada thistle shoots·m^{-2}; ΔY = change in total herbage yield from 1999 to 2000, or 1999 to 2001; ΔX = number of Canada thistle shoots·m^{-2} removed in 2000.

4. INTEGRATED EFFECTS OF FERTILIZATION WITH HERBICIDE AND MOWING TREATMENTS ON CANADA THISTLE ABUNDANCE AND PASTURE FORAGE PRODUCTION

4.1 Introduction

Canada thistle (*Cirsium arvense* L. Scop) is a widespread, aggressive, perennial weed of agricultural areas in Canada and the northern United States (Alex 1966; Donald 1990; Skinner et al. 2000). In Canada it is found in all provinces as far north as 59°, and in Alberta, was reported in 53% of all cereal and oilseed fields surveyed during 1997 (Moore 1975; Thomas et al. 1998). The limited surveys of weeds in forage crops of western Canada indicate that Canada thistle is prevalent in alfalfa (*Medicago sativa* L.) seed fields as well as pasture and hay land (Thomas and Wise 1983; Goodwin et al. 1986).

In southern Alberta, Canada thistle decreased alfalfa seed yields (Moyer et al. 1991), and in pastures, likely reduces forage biomass through plant competition and allelopathy (Bendall 1975; Stachon and Zimdahl 1980; Wilson 1981). In addition, Canada thistle reduces pasture utilization by grazing animals, likely a result of its unpalatable nature associated with its spiny morphology (Schreiber 1967; Hartley and James 1979).

Combining two or more treatments at once within an integrated management strategy may provide more effective control of Canada thistle in pastures or rangeland than each treatment applied alone (Apple and Smith 1976; Benz et al. 1999; Zimdahl

1999; Beck and Sebastian 2000; Masters and Sheley 2001; Sutherland 2001). Management tools readily available to producers that could be integrated to provide longer-term control of Canada thistle in forage crops include mowing, herbicides, and the use of fertilizers to enhance crop competition.

Mowing has been used to control Canada thistle infestations by preventing seed formation and weakening thistle plants by reducing carbohydrate assimilation and storage (Detmers 1927). Repeated mowing reduced Canada thistle infestations in alfalfa hay fields in the northern United States (e.g., Welton et al. 1929; Hodgson 1958, 1968; Schreiber 1967) while infrequent mowing (e.g., mowing once each year) did not provide longer-term control of Canada thistle in pastures of Victoria, Australia (Amor and Harris 1977).

Herbicides used for Canada thistle control include, among others, 2,4-D, (2,4-dichlorophenoxy acetic acid), dicamba, (3,6-dichloro-2-methoxybenzoic acid), picloram, (4-amino-3,5,6-trichloro-2-pyridinecarboxylic acid), and clopyralid, (3,6-dichloro-2-pyridinecarboxylic acid) (Donald 1990). Repeated applications of 2,4-D were required for longer-term suppression of Canada thistle in Ontario (Hay and Ouellette 1959) and Indiana (Schreiber 1967) pastures. Picloram, clopyralid, dicamba, and 2,4-D all reduced Canada thistle density and biomass in Nebraska pastures (Reece and Wilson 1983), while in grass seed crops of creeping red fescue (*Festuca rubra* L.) and timothy (*Phleum pratense* L.) in Alberta, picloram application resulted in significantly lower Canada thistle shoot densities than either 2,4-D ester or dicamba (Gallagher and Vanden Born 1976). In white clover (*Trifolium repens* L.) – perennial ryegrass (*Lolium perenne* L.) pastures in Australia, broadcast spraying with 2,4-D amine or ester did not reduce Canada

thistle shoot densities, while picloram+2,4-D gave control for two years (Amor and Harris 1977).

Suppression of Canada thistle through plant competition may be achieved through the seeding of alfalfa (e.g., Detmers 1927; Hodgson 1958; Ominski et al. 1999) or grasses (e.g., Wilson and Kachman 1999), or combining mowing with the seeding of competitive forages (e.g., Hodgson 1958; Derscheid et al. 1961; Thrasher et al. 1963). Alternatively, fertilization may enhance competition between desirable forage species and weeds (e.g., Sheley and Jacobs 1997; Cole 1998), although added nutrients may favor weed growth over crop growth, especially when initial weed density is high (DiTomaso 1995). Nitrogen fertilization decreased Canada thistle densities in irrigated Montana pastures (Thrasher et al. 1963) and acid grassland in the UK (Edwards et al. 2000), increased thistle density and biomass in Nebraska pastures (Reece and Wilson 1983), and had no effect in Ontario pastures (Hay and Ouellette 1959). Reasons for these inconsistencies are unclear, but may be related to climate, vegetation and soil type, initial nitrogen concentration and distribution in the soil, or the form of nitrogen applied (e.g., ammonium nitrate or urea).

In western Canada, information on the utility of integrated approaches to controlling Canada thistle in permanent pastures is lacking. The objectives of this research were to compare the effects of one-time mowing or herbicide application, with and without annual spring fertilization, on Canada thistle abundance, forage yield and quality, and pasture vegetation composition over a 3-year period. We hypothesized that fertilization would enhance the control of herbicide-treated Canada thistle, as well as

result in greater increases in forage quality and yield, while fertilization alone or coupled with mowing would increase thistle abundance (density and biomass).

4.2 Materials and Methods

4.2.1 Study Sites

This research was conducted from 1999 to 2001 at four pasture sites situated throughout the Aspen Parkland of central Alberta (Table 4.1; Appendix 1.2). Pastures selected for the study met the following criteria: (1) they were relatively uniform in both physical conditions (e.g., soils and disturbance history) and forage sward composition, (2) they had a heavy infestation of Canada thistle, and (3) they had not been sprayed for at least 3 years prior to 1999. Sites were tame pastures dominated by combinations of grasses such as meadow brome (*Bromus biebersteinii* Roem. & Schult.), smooth brome (*Bromus inermis* Leyss.), Kentucky bluegrass (*Poa pratensis* L.), and quackgrass (*Agropyron repens* (L.) Beauv.) (Table 4.2). On average, forb production and legume cover was greater at Sites 3 and 4 than Sites 1 and 2, although at Site 4, forbs consisted of a larger number of native species (Table 4.3). Common forbs included dandelion (*Taraxacum officiniale* Web.), American vetch (*Vicea americana* Muhlenb.) and white clover (*Trifolium repens* L.). Overall, pasture production was greatest at Site 1, as it was situated on a river floodplain and contained nutrient-rich soils (Table 4.4). Among the four sites, Canada thistle shoot densities ranged from 22 to 51 shoots $\cdot m^{-2}$, and thistle biomass ranged from 381 to 3045 kg $\cdot ha^{-1}$, within the unfertilized check plots sampled in August 1999 (Table 4.4). At sites 3 and 4, two additional noxious weeds were present,

tall buttercup (*Ranunculus acris* L.) and perennial sow-thistle (*Sonchus arvensis* L.), respectively. At Site 3, percent cover of tall buttercup averaged 5%, while Site 4 contained an average of 31 shoots·m^{-2} and 134 kg·ha^{-1} of perennial sow-thistle.

At each site, an area approximately 100 by 60 m was fenced to exclude livestock, and soil samples collected in May 1999 to provide base-line information on physical site characteristics and establish fertilization recommendations (Table 4.4). Soils were sub-sampled at four points randomly distributed throughout each of the four, unfertilized check plots, and then pooled prior to lab analysis. Two depths were sampled (0-15 and 15-30 cm), with each depth analyzed separately, and the results of the two averaged following analysis. Nitrogen (nitrate), phosphorus (phosphate), and potassium analyses were conducted according to the methods of Ashworth and Mrazek (1995). Sulfur (sulfate), organic matter, pH, electrical conductivity, and particle size were determined using the methods of McKeague (1978). Soil pH ranged from 6.0 to 7.9, organic matter from 10.1 to 33.5%, and electrical conductivity from 0.2 to 2.9 mS/cm (Table 4.4). Soils were classified in September of 2001, with three sites determined to be Chernozems and the fourth, a Humic Gleysol (Table 4.4; Appendices 2.1-2.4). All soil textures were loamy.

Precipitation data were collected for all four sites for each of 1999, 2000, and 2001 (Table 4.1).

4.2.2 Experimental Design

The experiment was conducted using a split-plot, randomized complete block design with four replications of each treatment at every pasture site. Main plots (5 by 20

m) were randomly assigned the following treatments: (i) an untreated check, (ii) mowing, (iii) 2,4-D ester at 1.65 kg·ha^{-1}, (iv) 2,4-D + mecoprop + dicamba at 0.96 + 0.26 + 0.36 kg·ha^{-1}, respectively, (v) clopyralid at 0.22 kg·ha^{-1}, and (vi) picloram + 2,4-D at 0.24 + 0.89 kg·ha^{-1}, respectively. Herbicide rates were approximately mid-range in the window of recommended rates for Canada thistle control in pastures (Alberta Agriculture, Food, and Rural Development 2003). Each main plot was split into two sub-plots (each 5 by 10 m) with one randomly assigned the fertilization treatment. Based on annual soil test recommendations for the most nutrient limited sites, fertilized sub-plots were treated with 375 kg·ha^{-1} of blended complete fertilizer (29-13-3-4, NPKS), for a total of 112-50-11-17 kg·ha^{-1} in June of 1999 (Table 4.5). The form of N, P, K, and S applied were ammonium (urea), phosphate (ammonium-phosphate), potash (K_20), and sulfate (ammonium-sulfate), respectively. The fertilizer blend was intended to eliminate all plant macronutrient deficiencies at each site to maximize forage responses in association with thistle removal.

Mowing and herbicide applications were conducted in July of 1999, when the majority of Canada thistle plants were at the early bud stage of growth, and were carried out only once during the course of the three-year study (Table 4.5). Mowing was carried out using a sickle bar in a manner similar to haying, with thistles cut at a height of 5 cm. Herbage and thistle biomass were removed from mowed plots to prevent vegetation smothering, and therefore, simulated a conventional haying operation. Herbicides were broadcast sprayed with a CO_2 sprayer mounted on a 3-point hitch on a Kobota tractor using 80 degree, flat fan nozzles at 75 kPa delivering 100 L of spray solution ha^{-1}.

Soils in fertilized check plots were again sampled in early May of 2000 and 2001, and upon analysis, several sites were found to be deficient in the same macronutrients

and to the same magnitude as in 1999. As a result, the same amount and proportion of fertilizer was applied to all fertilized sub-plots in May of each year.

4.2.3 Vegetation Sampling and Forage Quality Analysis

At peak vegetation growth in late August or early September of 1999, plots were sampled for above-ground, annual net primary production (ANPP). Percent thistle control (visual estimates), live thistle density and biomass, as well as forage production (separated into grass and forb) and species composition (ocular cover estimates) were determined in 4, 0.5 by 0.5 m (0.25 m^2) quadrats (sub-samples) within each sub-plot. The 4 quadrats were positioned every 2 m along a randomly placed transect through each sub-plot. Thistle control was not assessed in mowed plots because of the recent and destructive nature of treatment, as well as the high level of thistle re-growth observed following treatment. All sampling took place inside a 1-meter buffer from the edge of each sub-plot to avoid edge effects from adjacent plots. Because Site 4 contained an appreciable amount of sow-thistle, plots at this site were sampled for sow-thistle abundance to test whether the same treatments would be effective for controlling sow-thistle. Following vegetation sampling in August, cattle were permitted to graze all study plots in order to remove litter and maintain conventional pasture use.

Harvested sub-samples (thistle, grass, and forb) were pooled for each sub-plot, oven-dried at 60°C to constant mass, and weighed. Forage (grass and forb) samples from 1999 were then ground through a 1 mm Wiley mill, and quality analyses (crude protein, acid detergent fiber, and phosphorus) carried out on all treatments except mowed plots. Quality analyses on herbage re-growth in mowed plots would have confounded

comparison to the other treatments, as mowed plots were essentially re-growth. Total nitrogen content was determined using a Leco nitrogen analyzer (Leco Corporation 1992). Crude protein content of herbage was determined by multiplying percent nitrogen by 6.25. Acid detergent fiber (ADF) was determined using the filter bag technique (Komarek 1993). Phosphorus was determined according to the methods of Helrich (1990). In 1999, forage quality was determined for both grass and forb samples at Sites 3 and 4 because of the relatively large proportion of forbs at these locations (14 and 26% of total herbage production, respectively; Table 4.3). However, because of the very low forb production at Sites 1 and 2 (i.e., < 5% of the total herbage production, Table 4.3), only grass samples at these sites were analyzed for forage quality.

At peak vegetation growth in August 2000, herbage and Canada thistle were again sampled at all sites using the same procedure as the previous year. In 2000, due to time constraints and low overall sow-thistle abundance at Site 4, only sow-thistle cover was assessed. Forage quality analyses (crude protein and ADF only) were again carried out on grass and forb samples from Sites 3 and 4, and on grass samples from Sites 1 and 2.

In August of 2001, vegetation was again sampled at all locations except Site 3, which was broken into by cattle in late July and heavily grazed. Although Canada thistle and herbage did not re-grow sufficiently to warrant biomass sampling, thistle shoot density and vegetation composition were assessed in mid-September from the limited re-growth that did occur (Table 4.5). At Site 4, sow-thistle biomass was quantified in 2001. Forage quality analyses (crude protein and ADF) were again carried out on grass samples from Sites 1, 2, and 4, but because of the very low forb production in 2001, there was insufficient biomass to conduct quality analyses on forbs from Site 4.

4.2.4 Analysis

All data were analyzed using a split-plot analysis of variance (ANOVA) to evaluate the effects of method of Canada thistle control (i.e., main plot), fertilization treatments (i.e., sub-plots), as well as thistle control by fertilization interactions. Repeated measures ANOVA was not used to test for a year effect because of the discontinuity in thistle, grass, and forb production data that resulted from cattle breaking into the pasture at Site 3 in July of 2001. In addition, spring and early summer precipitation was markedly lower in 2001 than in the two previous years and was followed by very heavy rainfall at some locations, which resulted in considerably lower vegetation production in 2001 than during the two previous years. As a result, data were analyzed separately for each year, with pasture sites analyzed as blocks. This procedure tested for the longevity of each treatment effect on a year-to-year basis.

Vegetation variables analyzed included Canada thistle density and biomass, as well as forb and grass biomass at all four sites. Tall buttercup percent cover from Site 3 and sow-thistle density and biomass from Site 4 were also assessed. Vegetation cover composition data were used to evaluate species richness (# species per unit area) and diversity (Shannon's index), along with legume and native species cover at select sites (i.e., where found). Shannon's diversity index was calculated according to the formula, diversity $= -\sum_{i=1}^{s} p_i \ln p_i$, where s = number of species, p_i = the proportion of individuals or the abundance of the ith species expressed as a proportion of total cover, and ln = log base_n (Kent and Coker 1992). Legume cover was analyzed only at Sites 3 and 4 because legumes were lacking at Site 1 and very sparse at Site 2 (Table 4.3). Forage quality

variables analyzed were crude protein, ADF, phosphorus (1999 only), and crude protein yield (calculated by multiplying grass and forb yield by percent crude protein).

All data were checked for normality prior to ANOVA through examination of plots of the residuals, and tests of the Shapiro–Wilks' statistic (SAS Institute Inc. 1988). Canada thistle density, biomass, and biomass per stem were square-root transformed for 1999 and 2000, and log(X+1) transformed for 2001. Species diversity for 1999 was log(X+1) transformed as well. Post-hoc mean comparisons were performed on all significant thistle control, fertilization, and control by fertilization interactions based on the F test results ($P < 0.05$ for the main effects, and 0.10 for interactions). A less conservative significance value was chosen for interactions because of the greater potential difficulty in detecting these effects compared to main effects. Mean comparisons were conducted using Tukey's method ($P < 0.05$) (Zar 1996; Steel et al. 1997).

4.3 Results

Precipitation at all sites was markedly lower in the spring and early summer of 2001 compared to 1999 and 2000 (Table 4.1). Although total summer precipitation in 2001 was generally greater than previous years, the majority came late in the summer (i.e., late July and early-mid August, data not shown) and occurred as heavy thunderstorms at some locations (especially Sites 1 and 2). This variation in growing conditions among years was reflected in the apparent decrease in thistle shoot density and

biomass in untreated, check plots during 2001 compared to the other years (Tables 4.6, 4.7).

Block by thistle control treatment effects were significant ($P<0.01$) for a number of thistle variables in some or all years of the experiment (Tables 4.6, 4.7), as well as forb biomass (Table 4.9) and some forb forage quality variables in 1999 and 2000 (Tables 4.12, 4.13). Given that the relative ranking among treatments within blocks typically remained the same (data not shown), these effects were likely caused by subtle differences in the magnitude of specific treatment responses within individual sites.

4.3.1 Canada Thistle Control

In 1999, 2000, and 2001, thistle control treatment significantly affected ($P<0.001$) all thistle variables (Tables 4.6, 4.7). Herbicide treatment by fertilizer interactions were also significant ($P<0.10$) for thistle density in 2000 and 2001 (Table 4.6), and thistle biomass in 1999, 2000, and 2001 (Table 4.7).

In 1999, herbicide application resulted in greater thistle control (% visual estimates) than untreated plots, leading to decreased Canada thistle density (Table 4.6) and biomass (Table 4.7). Among herbicide treatments, 2,4-D plots had lower thistle control compared to the other herbicides (Table 4.6). Clopyralid and picloram +2,4-D resulted in greater reductions in thistle density and biomass compared to 2,4-D alone.

During 2000, thistle density and biomass remained lower on herbicide treated plots, although some herbicides had less thistle than others. In particular, residual thistle density and biomass were lower on clopyralid and picloram+2,4-D plots compared to plots of 2,4-D, and these differences remained evident a year later in 2001 (Tables 4.6,

4.7). In addition, individual thistle stem biomass was lowest on clopyralid and picloram+2,4-D plots in 2001 (Table 4.7).

Fertilization increased thistle biomass in check plots in 1999 (Table 4.7). Despite the overall decrease in thistle biomass after 1999 due to drier conditions, thistle biomass remained higher on fertilized check plots in 2000 and 2001, although this difference was not significant in the latter (Table 4.7). Greater thistle biomass in fertilized check plots in 2000 was despite a reduction in the number of thistle plants with fertilization (Table 4.6), a trend that continued into 2001 (Table 4.6). Within many of the herbicide treatments, fertilization decreased thistle density (Table 4.6) and biomass (Table 4.7), and this became even more apparent in 2001. The exception was 2,4-D+mecoprop+dicamba, which did not lead to significant ($P<0.05$) reductions in thistle biomass with fertilization in either 2000 or 2001 (Table 4.7), although these plots did have consistently lower thistle densities with fertilization in all three years (Table 4.6).

Mowing increased thistle shoot density relative to the check (Table 4.6) and, as might be expected, decreased biomass relative to untreated plots in August of 1999 (Table 4.7). Vigorous re-growth in 1999 was evident in mowed plots as numerous, young shoots, and was reflected in the low thistle biomass per stem (Table 4.7). In 1999, 2000 and 2001, fertilization significantly increased thistle biomass on mowed plots ($P<0.05$; Table 4.7). This increase with fertilization was greatest in 2000, likely as a result of both the increased stem density that occurred in mowed plots the year before, as well as the removal of litter and other vegetation.

4.3.2 Tall Buttercup and Perennial Sow-thistle Control

Tall buttercup was not sufficiently abundant in 2000 and 2001 to enable a reliable statistical analysis. In 1999, herbicides and fertilization generally decreased tall buttercup cover at Site 3, but reductions were not significant ($P>0.05$; Table 4.8). Thistle control treatment significantly affected ($P<0.05$) perennial sow-thistle density and biomass at Site 4 in 1999 (Table 4.8). Although all herbicides appeared to reduce sow-thistle density and biomass, reductions were only significant ($P<0.05$) for 2,4-D (Table 4.8). Fertilization also increased sow-thistle biomass in 1999 ($P<0.05$), although this appeared to occur primarily in the check plots (Table 4.8). Two years later in 2001, annual fertilization had reduced sow-thistle biomass on these same check plots.

4.3.3 Forage Production Responses

Significant herbicide treatment (whole-plot) effects ($P<0.001$) were evident for grass biomass in 2000 and forb biomass in 1999 and 2000, but not in 2001 (Table 4.9). In 1999, forbs decreased with herbicide application. One year later, herbicides increased grass biomass with an associated decrease in forb biomass relative to the untreated check (Table 4.9). Mowed plots did not reduce forb biomass relative to the check in 2000 (Table 4.9).

Fertilization increased grass biomass in all 3 years of monitoring (Table 4.9). This trend was accompanied by a decrease in forbs, although only the decrease in 2000 was significant ($P<0.001$; Table 4.9). The lack of a treatment by fertilizer interaction effect on grass biomass in any year indicated the fertilization effect was consistent among

treatments. In 2000, mowed plots had significantly greater ($P<0.05$) forb biomass in unfertilized plots (Table 4.9). This trend was again evident in 2001.

4.3.4 Forage Quality Responses

In 1999, method of thistle control had no effect on grass quality (crude protein or ADF; Tables 4.10, 4.11), but as expected, fertilization increased quality (phosphorus, crude protein content and yield).

In 2000, fertilization increased both grass crude protein content and crude protein yield, while herbicide application increased only the crude protein yield of grasses (Table 4.10). In 2001, fertilization again increased grass quality, including crude protein yield, but had similar effects within each of the thistle control treatments.

Herbicide application decreased forb crude protein content and crude protein yield in 1999, with an additional decrease evident in 3 of 4 herbicides for crude protein content and crude protein yield in 2000 (Table 4.12). In the same year, ADF decreased (i.e., quality increased) with 3 of 4 herbicide treatments (Table 4.13). Notably, fertilization increased ADF in 1999 and 2000 (Table 4.13), and decreased crude protein in 2000.

Treatment by fertilization interactions ($P<0.10$) were found for forb crude protein in 1999 and all forb quality variables in 2000 (Tables 4.12, 4.13). Effects of fertilization on forb crude protein content and yield within the herbicide plots in 1999 and 2000 varied, and were not consistent among herbicides (Table 4.12). Within the herbicide plots, forb ADF generally increased with fertilization in 2000, with the exception of picloram+2,4-D, which resulted in lower forb ADF under fertilization (Table 4.13).

4.3.5 Species Composition Responses

Overall, species richness and diversity were low throughout the three years of the study (Kent and Coker 1992), likely because all sites were tame pastures dominated by only a few grass species (Tables 4.2, 4.3). Nevertheless, herbicides generally decreased richness, diversity, and native as well as legume cover in 1999 (Tables 4.14, 4.15). These effects continued into 2000 and 2001, although they weakened in the last year.

Fertilization also decreased richness, diversity, and legume cover throughout most of the study years, although no difference in legume cover was found in 2001 (Tables 4.14, 4.15). No change in native species cover was found with fertilization from 1999 to 2001 (Table 4.15).

In 2000, there was a significant thistle control treatment by fertilization interaction ($P<0.10$) for both diversity (Table 4.14) and legume cover (Table 4.15). The greatest decrease in diversity in 2000 appeared to occur with the combination of fertilizer and herbicide application (Table 4.14). The decrease in legume cover with fertilization in 1999 and 2000 was limited only to the check and mowed plots (Table 4.15).

4.4 Discussion

To date, efforts at developing integrated strategies for thistle control in pastures have focused primarily on coupling biological control agents with plant competition (e.g., Trumble and Kok 1982; Ang et al. 1994a,b, 1995), although a few studies have addressed the utility of combining herbicides with fertilizer (e.g., Hay and Ouellette 1959; Reece

and Wilson 1983) or mowing (Beck and Sebastian 2000). Ultimately, the effects on Canada thistle control in pasture have varied.

While frequent mowing (e.g., 2– 3 mows per year) has been shown to suppress Canada thistle (e.g., Welton et al. 1929; Hodgson 1958, 1968; Schreiber 1967), producers in western Canada will commonly mow thistle patches in pastures once per growing season, or occasionally as required by law to prevent noxious weeds from going to seed. Rarely is repeated mowing used as a concerted effort to eradicate thistle. Our results from 1999 to 2001 demonstrated that one-time mowing did not provide longer-term control of Canada thistle, and actually increased thistle density in the short term. Cutting likely stimulated the growth of Canada thistle shoots from adventitious root buds or from lateral buds on underground stems, resulting in increased thistle densities in the year of mowing, and marked increases in thistle biomass with fertilization in the second year of the experiment. Amor and Harris (1977) also found that longer-term control of Canada thistle was unsuccessful with annual mowing in perennial ryegrass / white clover pastures in Victoria, Australia. While Donald (1988) reported an increase in Canada thistle shoot density with cutting in greenhouse experiments, documented effects of mowing in field trials appear to be lacking. Our research provides evidence of the rapid, marked thistle shoot increases that occur following occasional mowing in western Canadian pastures.

Clopyralid and picloram+2,4-D consistently resulted in the greatest longer-term control of Canada thistle, followed by 2,4-D+mecoprop+dicamba and 2,4-D. These results are in agreement with greenhouse experiments by Hunter and Smith (1972), and field trials conducted in forages by Gallagher and Vanden Born (1976), Amor and Harris (1977), and Peterson and Parochetti (1978), who reported greater control of Canada

thistle with picloram than either 2,4-D or dicamba. Additionally, Reece and Wilson (1983) found that both clopyralid and picloram eliminated Canada thistle in pastures, while 2,4-D and dicamba did not.

The efficacy of both clopyralid and picloram has been attributed to their rapid absorption, uptake, and translocation throughout the thistle plant resulting in severe root damage or kill (e.g., Sharma et al. 1971; Hunter and Smith 1972; O'Sullivan and Kossatz 1982, 1984; Turnbull and Stephenson 1985). Picloram and clopyralid are related molecules (i.e., both are picolinic acids; Masters and Sheley 2001) and as a result, their effects on Canada thistle are similar (Donald 1990). For example, picloram and clopyralid both reduce thistle root biomass and bud numbers (Hunter and Smith 1972; Donald 1988), and picloram reduces the length of thistle roots (Lauridson et al. 1983). In contrast, dicamba and 2,4-D cause more rapid leaf and shoot tissue damage after application, resulting in shorter-term top-growth control of thistle, but limited root kill, likely because of impaired translocation as a result of rapid xylem and phloem destruction (Chang and Vanden Born 1968; Hunter and Smith 1972). Improved control of Canada thistle with dicamba compared to 2,4-D may be attributable to better translocation (e.g., Chang and Vanden Born 1968) or more likely, greater phytotoxicity to thistle plants.

The longer-term thistle reductions with clopyralid and picloram+2,4-D were likely a result of better initial root kill and/or inhibition of thistle re-growth through residual soil chemical effects. Picloram is persistent and can remain in the soil for 5 or more years following treatment (Herr et al. 1966; Vanden Born 1969; Phillips and Feltner 1972). While clopyralid is less persistent, it can have soil residual activity for 1 or more

years following application, and may initially be more phytotoxic to thistle plants than picloram, as lower rates of clopyralid provide similar control to higher rates of picloram (O'Sullivan and Kossatz 1984; Turnbull and Stephenson 1985; Alberta Agriculture, Food, and Rural Development 2003). In contrast, 2,4-D and dicamba have less substantial soil residual effects, as there are fewer cropping restrictions for these herbicides the year after application (Alberta Agriculture, Food, and Rural Development 2003).

The observed increase in grass biomass during 2000 following herbicide application was in agreement with Reece and Wilson (1983), who reported that thistle reductions caused by clopyralid, picloram, and dicamba also increased grass biomass in Nebraska pastures. In contrast, Hay and Ouellette (1959) found that Canada thistle reductions with 2,4-D did not increase total herbage biomass in Quebec pastures. The reduction in non-thistle forb biomass with herbicides in the present experiment was expected, as all the chemicals tested here are reported to affect a wide range of broadleaf plants (Alberta Agriculture, Food, and Rural Development 2003).

The apparent weakening of herbicide effects on Canada thistle and herbage in 2001 may have reflected declining residual thistle control over the longer-term, or could be attributed to the drought-like conditions experienced in the early spring and summer of 2001 compared to previous years. While more substantial precipitation events occurred in late July and early to mid August of 2001, it is likely that low precipitation had already impeded thistle growth by the time of vegetation sampling in early August. Canada thistle is particularly sensitive to the warm, dry conditions that accompany drought, and will often demonstrate reduced growth during periods of low precipitation (Moore 1975).

Drought effects were evident through a decrease in thistle biomass on unfertilized check plots from 1337 kg·ha^{-1} in 1999, to 127 kg·ha^{-1} in 2001 (Table 4.7). It is possible that with more moisture in 2001, observed residual herbicide effects may have been more pronounced.

The marked increase in thistle biomass with fertilization in the present experiment is in agreement with Nadeau (1988) and Nadeau and Vanden Born (1990), who reported increased Canada thistle shoot production with nitrogen addition, as well as Reece and Wilson (1983), who found that nitrogen fertilization in the absence of thistle control increased Canada thistle abundance in permanent Nebraska pastures. Without any associated measures for controlling the weed, Canada thistle plants likely benefit from fertilization by directly increasing plant growth and opportunistically using other available resources (e.g., light and water). At Site 4, fertilization also increased perennial sow-thistle in the year of application, but enhanced grass growth with fertilization in subsequent years eventually out-competed the shorter, less vigorous sow-thistle plants (Table 4.8). In contrast, the utility of fertilization for suppressing Canada thistle in pastures without the combined use of thistle control measures is questionable.

The increase in grass vigor, growth, and biomass with annual, spring fertilization from 1999 to 2001, improved thistle control with herbicides, likely through enhanced competition. These results contrast with those of Reece and Wilson (1983), who found that nitrogen fertilization led to non-significant increases in grass production, and when coupled with 2,4-D, dicamba, clopyralid, or picloram application, did not enhance competition with Canada thistle. Hay and Ouellette (1959) found that when fertilization was coupled with 2,4-D treatment, forage production was enhanced, but thistle control

was not improved compared to 2,4-D applied alone. Differences between the present experiment and the studies by Hay and Ouellette (1959) and Reece and Wilson (1983) may be due to environmental differences, including soils, growing season precipitation, or pasture vegetation composition between Ontario and Nebraska, respectively, and central Alberta.

In the present study, the increase in grass biomass that resulted from fertilization and herbicide application did so at the expense of forbs. Grasses responded to nitrogen fertilization more readily than legumes and other forbs, which is consistent with the current literature (e.g., Miller and Reetz 1995). Moreover, forbs reduced by herbicide application were likely further reduced by increased grass competition in fertilized plots.

Greater crude protein content and yield indicate greater forage quality. In contrast, greater ADF indicates lower energy feed. Increases in grass crude protein content and yield with fertilization are well documented (e.g. Miller and Reetz 1995), and were therefore expected and observed from 1999 to 2001 in the current experiment. However, few published studies have looked at forage quality effects when integrated approaches combining fertilizers and herbicides are used to control Canada thistle in pastures.

Hay and Ouellette (1959) suggested that 2,4-D applied to control Canada thistle increased forage quality by decreasing the content of thistle and other weeds, but quality variables were not directly measured. Reece and Wilson (1983) quantified the effects of fertilization and herbicides used to control Canada thistle in pasture on grass crude protein content and digestibility (estimated by in vitro dry-matter disappearance, IVDMD). Those authors reported that grass crude protein tended to increase with

fertilization, and that fertilized picloram and 2,4-D plots resulted in the greatest digestibility. However, few differences in crude protein were found among herbicide treatments (Reece and Wilson 1983). This is in agreement with our findings, with the exception that in 2000, grass crude protein yield increased following herbicide application, primarily not from increased crude protein, but from increased grass biomass.

The increase in grass ADF with fertilization in 2000 and 2001 may have been a result of drought stress, or possibly a result of increased stem tissue in grasses of fertilized plots (Table 4.11). Grass plants were markedly taller in fertilized plots compared to unfertilized plots, which was likely a result of both higher soil nutrients and increased competition with neighboring plants. These taller grasses likely had a higher proportion of fiber-rich stem tissue compared to lower-fiber containing leaf tissue. While increases in grass ADF content with fertilization were significant in 2000 and 2001, differences were less than 2% (e.g., 43.1 vs. 45.0% and 44.1 vs. 44.8%, respectively).

In the present experiment, the decrease in crude protein content and yield of forbs with herbicide and fertilizer application (Table 4.12) was likely a result of the removal of high quality forbs such as legumes, which was evidenced by the decrease in forbs and legume cover with both types of treatment (Tables 4.9, 4.15). The increase in forb ADF content caused by fertilization (Table 4.13) may also have been a result of the removal of higher quality forbs such as legumes. In addition, increased competition from neighboring grasses may have led to increased forb ADF. As the grasses grew taller and more vigorous with fertilization, any remaining forbs would have had to put more growth

into higher fiber-containing stems, in an attempt to access more light through the grass canopy, or alternatively, begin senescence earlier.

The reduction in species richness, diversity, and legume cover with herbicide treatment appeared to be the result of forb removal in 1999. These effects continued into 2000 and 2001, although they weakened in the last year of monitoring, owing to either dry conditions or the effects dissipating 2 years after the one-time thistle control treatments. Picloram+2,4-D reduced legumes to the greatest extent, with legumes almost eliminated in these plots by 2000 and 2001. These results agree with Amor and Harris (1977), who reported that broadcast spray applications of picloram+2,4-D at 0.25 to 0.5 $kg \cdot ha^{-1}$ eliminated white clover from perennial ryegrass pastures in Australia. The same study also found that ester and amine formulations of 2,4-D at 2 $kg \cdot ha^{-1}$ significantly reduced white clover for up to two years following herbicide application. Although Hay and Ouellette (1959) found that 2,4-D ester at 1.12 $kg \cdot ha^{-1}$ "injured white clover", they did not quantify the level of damage. Peterson and Parochetti (1978) found that picloram at 0.56 and 1.12 $kg \cdot ha^{-1}$ eliminated red clover in Maryland timothy pastures, which is consistent with our results using picloram+2,4-D at 0.24 + 0.89 $kg \cdot ha^{-1}$. The previous authors also found that dicamba at 0.56 and 1.12 $kg \cdot ha^{-1}$ reduced red clover by 57 and 82%, respectively, while 2,4-D amine at 0.84 and 1.68 $kg \cdot ha^{-1}$ reduced red clover by 47 and 55%, respectively. Our results with 2,4-D and 2,4-D+mecoprop+dicamba are generally in agreement with Peterson and Parochetti (1978), in that similar rates of these herbicides significantly reduced legumes.

The decrease in species richness and diversity with fertilization was expected, as the fertilization regime used consisted of a heavy nitrogen application, which has been

shown to favor grass growth over legumes and other forbs (Miller and Reetz 1995). Legumes and other forbs generally respond better to phosphorus and potassium additions, while nitrogen fertilization may lead to indifferent yield responses or even a decrease in legumes directly through the reduction of rhizobial activity and nitrogen fixation within nodules (Miller and Reetz 1995). The visible increase in grass biomass with fertilization also likely led to increased competition with the less-vigorous and lower-statured legumes and other forbs. Overall, the greatest decrease in diversity occurred in 2000 on fertilized and herbicide treated plots (Table 4.14), likely because herbicides reduced forbs in 1999, and fertilization subsequently favored grass growth over forbs.

The observed decrease in species richness, diversity, and legume cover with fertilization is consistent with numerous ecological studies and the widely held belief among ecologists that increased environmental productivity with fertilization generally reduces species richness and diversity (Begon et al. 1990). While the trend within Sites 2 and 3 was for non-significantly lower ($P>0.10$) native species cover with fertilization, at Site 4, fertilization had no effect on American vetch, which was the dominant native species present (data not shown). As a result, overall, native species cover was not affected by fertilization in the present experiment, which may have been partly the result of the low overall presence of native species, or because increased competition from grasses as a result of fertilization may not have been enough to outcompete and remove the native species present.

4.5 Conclusions and Management Recommendations

The future potential for longer-term control of Canada thistle in pastures and hay land will most likely be achieved through an integrated approach that takes into account both the biology of Canada thistle and the forage sward, as well as practical environmental and economic concerns. The present study determined if one-time herbicide application or mowing could provide effective control of Canada thistle in pastures, and whether annual, spring application of N, P, K, and S fertilizer to soil test recommendation would affect this control, including its longevity.

Fertilization in the absence of any control measures increased forage yield and quality, but also increased Canada thistle abundance. A one-time mowing treatment did not provide suppression of Canada thistle, and actually increased Canada thistle shoot densities in the year of treatment. Producers who use occasional mowing as an emergency treatment for Canada thistle control may therefore be increasing thistle abundance in their pastures over the long-term. Fertilization of mowed plots further exacerbated the problem by increasing Canada thistle biomass. Our results indicate that Canada thistle is well-adapted to utilize nutrients added through fertilizer. Thus, pasture fertilization and infrequent mowing, either alone or in combination with each other, are not recommended if Canada thistle control is a management objective.

One-time application of herbicides resulted in the suppression of Canada thistle in the year of treatment, regardless of whether herbicides were combined with fertilization. However, subsequent spring fertilization was important for enhancing the longer-term, residual control of Canada thistle by herbicides. While thistle showed considerable signs of recovery in unfertilized plots in the second and third years of the experiment, fertilized

plots gave rise to healthier, more vigorous grass stands that provided increased competition with, and suppression of, Canada thistle. Herbicides reduced forbs to varying levels, but this reduction was more pronounced with fertilization, which favored grass over forb growth.

Picloram+2,4-D at 0.24 + 0.89 kg·ha^{-1} and clopyralid at 0.22 kg·ha^{-1}, applied at the early bud stage of Canada thistle growth, combined with spring fertilization, provided the greatest, 3-year suppression of Canada thistle. However, both 2,4-D at 1.65 kg·ha^{-1} and 2,4-D+mecoprop+dicamba at 0.96 + 0.26 + 0.36 kg·ha^{-1}, applied at the early bud stage of Canada thistle growth, also suppressed Canada thistle over this period. All herbicides reduced forbs, including legumes, but picloram+2,4-D coupled with fertilization eliminated legumes by the second and third year of the study, likely because of picloram's soil persistence. Herbicide use, particularly when combined with annual, spring fertilization, increased grass yield and quality, but also decreased forb yield and quality. Reductions in the forb component may have been offset by increased grass quality and production.

Specific recommendations for thistle control will ultimately vary depending on forage sward composition and management objectives. If maintaining species diversity is a management objective, the use of herbicides may not be an appropriate part of a control strategy, as most herbicides reduced species richness, diversity, and native species cover. Additionally, Canada thistle-infested pastures dominated by grasses but containing a large proportion of desirable legumes may be more difficult to manage if maintaining legumes is a high priority. All herbicides tested reduced legumes, and this effect was exacerbated when combined with fertilization. However, the enhanced residual control

of thistle, along with the associated increase in grass production and quality that results from fertilization, may offset losses in crude protein yield from the removal of legumes, and merits further research.

In permanent pastures where legumes are not abundant, annual spring fertilization combined with clopyralid or picloram + 2,4-D applied at the early bud stage appeared to provide the greatest reduction in Canada thistle, while simultaneously increasing grass production and crude protein yield. In dry years, when thistle abundance may be low, herbicides and fertilization may not suppress thistle growth and increase grass production enough to economically justify their application. In general, the choice of herbicide will ultimately be determined by cost, efficacy, residual concerns, and whether maintaining species diversity is a high priority.

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Table 4.1 Locations, landscape characteristics, and growing season precipitation for the four pasture research sites.

Site	Location	Lat / Lon	Slope / Aspect	Landform	Precipitation (May-August; mm)			
					1999	2000	2001	30-yr average
1	Barrhead	54° 00' 57" N 114° 22' 44" W	Level / NA	Floodplain	281	301	292	319
2	Lamont	53° 42' 24" N 112° 33' 10" W	Level / NA	Level moraine	235	272	279	263
3	Rocky Mountain House	52° 18' 55" N 114° 31' 48" W	< 2% / South	Rolling moraine	365	406	256	372
4	Two Hills	53° 47' 5" N 111° 27' 24" W	< 4% / West	Hummocky moraine	194	248	219	251

Table 4.2 Dominant plant species composition of the four pasture sites, as sampled in August 1999.

Site	Dominant Grass Species	Dominant Forb Species
1	Quackgrass (*Agropyron repens* (L.) Beauvois) Kentucky bluegrass (*Poa pratensis* L.) Meadow bromegrass (*Bromus biebersteinii* Roem. & Schult.)	Dandelion (*Taraxacum officinale* Web.)
2	Smooth brome (*Bromus inermis* Leyss.), Kentucky bluegrass	Dandelion Common yarrow (*Achillea millefolium* L.)
3	Quackgrass Kentucky bluegrass	Dandelion Tall buttercup (*Ranunculus acris* L.) American vetch (*Vicia Americana* Muhlenb.) White clover (*Trifolium repens* L.)
4	Smooth brome, Kentucky bluegrass	Dandelion Alfalfa (*Medicago sativa* L.) White clover American vetch

Table 4.3 Vegetation characteristics of the four pasture research sites, as sampled in August 1999[z].

Site	Canada thistle biomass ($kg \cdot ha^{-1}$)[y]	Canada thistle density (no. $shoots \cdot m^{-2}$)[y]	Herbage production ($kg \cdot ha^{-1}$) (% Grass, % Forbs)[x]	Legume cover (%)	Native species cover (%)	Species richness (no. species per m^2)	Diversity index (per m^2)
1	3045 ± 242 (2616–3581)	46 ± 4 (37–55)	4335 ± 809 (96, 4)	0	0	3 ± 0.3	0.75 ± 0.12
2	381 ± 71 (179–494)	25 ± 3 (20–33)	2470 ± 172 (97, 3)	0.1 ± 0.07	9 ± 8	6 ± 0.7	1.07 ± 0.12
3	580 ± 80 (407–788)	22 ± 5 (14–33)	3409 ± 357 (86, 14)	22 ± 5.1	3 ± 2	8 ± 0.8	1.59 ± 0.02
4	1281 ± 497 (477–2731)	51 ± 14 (26–88)	3357 ± 337 (74, 26)	33 ± 10	16 ± 9	10 ± 0.4	1.55 ± 0.11

[z]Values are means ± standard error, calculated from the unfertilized, check plots sampled ($N = 4$).
[y]Values in parentheses for Canada thistle variables represent the data range. Site 4 also contained an average of 31 $shoots \cdot m^{-2}$ and 134 $kg \cdot ha^{-1}$ of perennial sow-thistle, based on unfertilized, check plots sampled ($N = 4$).
[x]Values in parentheses are proportions of total herbage production made up of grass and non-thistle forbs, expressed as mean percentages.

Table 4.4 Soil characteristics of the four pasture research sites, as sampled in May 1999[z].

Site	pH	E.C. (mS/cm)	O.M. (%)	Nutrients (kg/ha)[y]				Texture (%)			Soil Type
				N	P	K	S	Sand	Silt	Clay	
1	6.7	2.9	33.5	130	11	1009	3289	49.2	33.3	17.5	Loam, Orthic Humic Gleysol
2	6.9	0.5	10.1	47	7	428	33	38.6	44.0	17.4	Loam, Orthic Black Chernozem
3	6.0	0.2	11.0	11	7	798	16	28.0	49.7	22.3	Silt Loam, Orthic Black Chernozem
4	7.9	0.7	23.0	52	0	601	73	34.4	46.0	19.6	Loam, Gleyed Dark Gray Chernozem

[z]All values represent the average of the two soil depths that were sampled and analyzed separately (0-15 and 15-30 cm). Nitrogen, phosphorus, and sulfur were present in the form of nitrate, phosphate, and sulfate, respectively.
[y]Nutrients represent pre-fertilization data.

Table 4.5 Dates of mowing and herbicide application, as well as fertilizer application and vegetation sampling for the three years of the thistle control study.

Site	Herbicide Application, in 1999	Mowing Dates, in 1999	Fertilization Dates			Sampling Dates		
			1999	2000	2001	1999	2000	2001
1	July 9	July 14	June 22	May 19	May 31	Aug. 19	Aug. 3	Aug. 13
2	July 12	July 15	June 17	May 18	May 24	Aug. 17	Aug. 1	July 30
3	July 20	July 19	June 21	May 26	June 1	Aug. 26	Aug. 21	Sept. 20[z]
4	July 12	July 15	June 18	May 23	May 24	Aug. 24	Aug. 9	Aug. 2

[z]In 2001, Site 3 was broken into by cattle in late July and grazed, so vegetation assessments were deferred to September in order to allow sufficient re-growth to warrant assessments of thistle density and vegetation composition.

Table 4.6 Means and pooled SEs, as well as ANOVA *F* test significance values for percent thistle control (visual estimates) and thistle shoot density by thistle control treatment, fertilization, and treatment X fertilization combinations, from 4 pasture sites in central Alberta for 1999 to 2001[z].

Source	df	% Control of Canada thistle[y]	Thistle Shoot Density (no. m^{-2})		
		1999	1999	2000	2001
Treatment	5	$F = 1137.25$	F=129.90	F=27.14	F=14.87
		$P < 0.001$	P<0.001	P<0.001	P<0.001
Untreated check (T1)		0c	35b	25a	15a
Mowing (T2)		n/a	54a	24a	13ab
2,4-D (T3)		85b	8c	15b	8bc
2,4-D+mecoprop+dicamba (T4)		92a	6cd	14b	8bc
Clopyralid (T5)		93a	4d	8c	5c
Picloram + 2,4-D (T6)		91a	3d	8c	5c
SE		1	2.3	1.5	1.3
Block X Treatment	15	F=0.79	F=2.54	F=3.13	F=2.71
		P=0.66	P<0.01	P<0.01	P<0.01
Block X Rep(Treat) – Error 1	72				
Fertilization	1	F=0.76	F=0.25	F=69.71	F=60.71
		P=0.39	P=0.62	P<0.001	P<0.001
Fertilized (F)		72	19	12	6
Unfertilized (UF)		72	18	20	12
SE		0.4	0.8	0.8	0.6
Treatment X Fertilization	5	F=0.32	F=0.56	F=3.86	F=2.30
		P=0.86	P=0.73	P<0.01	P=0.05
T1 X F		0	33	21b[x]	12
T1 X UF		0	36	28a	18
T2 X F		n/a	57	23	12
T2 X UF		n/a	52	24	14
T3 X F		86	8	8b	4b
T3 X UF		84	9	21a	12a
T4 X F		92	7	11b	6b
T4 X UF		92	6	18a	11a
T5 X F		93	4	4b	3b
T5 X UF		93	4	13a	8a
T6 X F		91	3	4b	2b
T6 X UF		90	3	13a	9a
SE		0.8	1.9	2.0	1.5
Block X Treatment X Fertilization	15	F=0.69	F=1.28	F=0.66	F=1.36
		P=0.75	P=0.24	P=0.81	P=0.19
Residual Error	72				

[z]Means and pooled SEs are calculated for untransformed data. Where applicable, Tukey's test (P<0.05) was used for intra-treatment comparisons. F statistics, P values, and mean comparisons of shoot density are based on square-root (1999 and 2000) and log(X+1) (2001) transformed data, and un-transformed data for % thistle control.

[y]Visual estimates of % control were not made on mowed treatments. Therefore, for this parameter, df were 4 (Treatment, Treatment X Fertilization), 12 (Block X Treatment, Block X Treatment X Fertilization), and 60 [Block X Rep(Treat), Residual Error].

[x]All interaction mean comparisons are between fertilized and unfertilized treatments within each method of thistle control, within each year. Means with different letters differ, at P<0.05.

Table 4.7 Means and pooled SEs, as well as ANOVA *F* test significance values for thistle biomass and thistle biomass per stem by thistle control treatment, fertilization, and treatment X fertilization combinations, from 4 pasture sites in central Alberta for 1999 to 2001[z].

Source	df	Thistle Biomass ($kg\,ha^{-1}$)			Thistle Biomass per stem ($g\,shoot^{-1}$)		
		1999	2000	2001[y]	1999	2000	2001[y]
Treatment	5	*F*=69.06	*F*=39.16	*F*=14.63	*F*=12.37	*F*=6.84	*F*=5.21
		P<0.001	*P*<0.001	*P*<0.001	*P*<0.001	*P*<0.001	*P*<0.001
Untreated check (T1)		1512a	565a	146a	4.16a	2.27b	0.93a
Mowing (T2)		262b	536a	166a	0.43c	1.64b	0.72ab
2,4-D (T3)		212bc	220b	54ab	1.72bc	4.19a	0.61ab
2,4-D+mecoprop+dicamba (T4)		132cd	151bc	50bc	0.94bc	1.51b	0.64ab
Clopyralid (T5)		86d	75d	16c	1.06bc	0.96b	0.38b
Picloram + 2,4-D (T6)		74d	111cd	20c	2.16b	1.90b	0.31b
SE		73	42	30	0.38	0.43	0.10
Block X Treatment	15	*F*=5.46	*F*=4.25	*F*=3.64	*F*=2.34	*F*=1.51	*F*=4.48
		P<0.001	*P*<0.001	*P*<0.01	*P*=0.01	*P*=0.13	*P*<0.01
Block X Rep(Treat) – Error 1	72						
Fertilization	1	*F*=0.28	*F*=0.66	*F*=8.98	*F*=0.35	*F*=7.37	*F*=2.20
		P=0.60	*P*=0.42	*P*<0.01	*P*=0.56	*P*<0.01	*P*=0.14
Fertilized (F)		395	304	81	1.84	2.53	0.65
Unfertilized (UF)		365	249	70	1.65	1.62	0.54
SE		31	23	12	0.22	0.24	0.05
Treatment X Fertilization	5	*F*=6.84	*F*=6.36	*F*=5.26	*F*=1.27	*F*=1.37	*F*=2.14
		P<0.001	*P*<0.001	*P*<0.01	*P*=0.29	*P*=0.25	*P*=0.08
T1 X F		1687a[x]	682a	166	5.07	2.80	1.16a
T1 X UF		1337b	448b	127	3.25	1.74	0.69b
T2 X F		323a	733a	237a	0.51	1.96	0.86
T2 X UF		201b	339b	95b	0.34	1.32	0.59
T3 X F		179b	172b	22b	1.57	5.55	0.56
T3 X UF		246a	269a	87a	1.87	2.82	0.66
T4 X F		53b	135	52	0.61	1.82	0.78
T4 X UF		210a	167	47	1.27	1.20	0.49
T5 X F		38b	34b	4b	1.16	0.91	0.38
T5 X UF		133a	117a	27a	0.96	1.00	0.38
T6 X F		88	67b	4b	2.10	2.16	0.18
T6 X UF		61	154a	34a	2.23	1.64	0.44
SE		75	57	29	0.54	0.58	0.13
Block X Treatment X Fertilization	15	*F*=1.38	*F*=0.71	*F*=2.60	*F*=0.70	*F*=1.00	*F*=1.38
		P=0.18	*P*=0.77	*P*=0.12	*P*=0.78	*P*=0.47	*P*=0.22
Residual Error	72						

[z]Means and pooled SEs are calculated for untransformed data. Where applicable, Tukey's test ($P<0.05$) was used for intra-treatment comparisons. *F* statistics, *P* values, and mean comparisons of thistle biomass are based on square-root (1999 and 2000) and log(X+1) (2001) transformed data, and un-transformed data for biomass per stem.

[y]Site 3 was lost in 2001, so thistle biomass and biomass per stem were based on three sites in 2001. Therefore, df were 10 (Block X Treatment, Block X Treatment X Fertilization) and 54 [Block X Rep(Treat), Residual Error].

[x]All interaction mean comparisons are between fertilized and unfertilized treatments within each method of thistle control, within each year. Means with different letters differ, at $P<0.05$.

Table 4.8 Means and pooled SEs, as well as ANOVA *F* test significance values for tall buttercup and perennial sow-thistle variables by thistle control treatment, fertilization, and treatment X fertilization combinations, from pasture Sites 3 and 4, respectively (Rocky Mountain House and Two Hills), for 1999 to 2001[z].

Source	df	1999			2000	2001
		Tall buttercup cover (%)	Sow-thistle density (no. m^{-2})	Sow-thistle biomass (kg ha^{-1})	Sow-thistle cover (%)	Sow-thistle biomass (kg ha^{-1})
Treatment	5	*F*=2.63	*F*=3.69	*F*=3.08	*F*=2.55	*F*=1.09
		P=0.08	*P*=0.02	*P*=0.04	*P*=0.07	*P*=0.41
Untreated check (T1)		5	35a[y]	269a	10	49
Mow (T2)		5	26ab	29ab	4	1
2,4-D (T3)		2	4b	18b	0	0
2,4-D+mecoprop+dicamba (T4)		2	13ab	145ab	3	21
Clopyralid (T5)		5	26ab	182ab	7	32
Picloram + 2,4-D (T6)		1	7ab	103ab	0	0
SE		1	6	55	2	19
Rep X Treatment – Error 1	15	*F*=0.72	*F*=1.97	*F*=1.85	*F*=1.77	*F*=1.17
		P=0.74	*P*=0.10	*P*=0.12	*P*=0.14	*P*=0.38
Fertilization	1	*F*=1.59	*F*=0.41	*F*=5.48	*F*=1.32	*F*=4.37
		P=0.23	*P*=0.53	*P*=0.03	*P*=0.27	*P*=0.05
Fertilized (F)		2	17	163	3	2
Unfertilized (UF)		4	20	86	5	32
SE		1	3	23	1	10
Treatment X Fertilization	5	*F*=0.92	*F*=0.72	*F*=1.62	*F*=0.73	*F*=0.93
		P=0.50	*P*=0.62	*P*=0.22	*P*=0.61	*P*=0.49
T1 X F		4	40	404a[x]	10	10b
T1 X UF		5	31	134b	9	88a
T2 X F		5	21	21	2	0
T2 X UF		5	31	37	6	3
T3 X F		1	7	19	0	0
T3 X UF		2	2	16	0	0
T4 X F		1	12	178	3	0
T4 X UF		2	15	113	2	41
T5 X F		1	21	212	3	0
T5 X UF		8	32	153	10	63
T6 X F		1	4	142	0	0
T6 X UF		0	10	64	0	0
SE		2	6	57	2	25
Residual Error	15					

[z]*F* statistics, *P* values, and mean comparisons of all sow-thistle variables are based on untransformed data.
[y]Where applicable, means within a column followed by the same letter are not significantly different at the *P*<0.05 level using Tukey's test.
[x]Within a column, fertilized and unfertilized treatment means with different letters differ, at *P*<0.05.

Table 4.9 Means and pooled SEs, as well as ANOVA *F* test significance values for grass and forb biomass by thistle control treatment, fertilization, and treatment X fertilization combinations, from 4 pasture sites in central Alberta for 1999 to 2001.

Source	df	Grass Biomass ($kg \cdot ha^{-1}$)			Forb Biomass ($kg \cdot ha^{-1}$)		
		1999	2000	2001[y]	1999	2000	2001[y]
Treatment	5	F=27.26	F=12.48	F=1.68	F=9,10	F=12.18	F=1.66
		P<0.001	P<0.001	P=0.15	P<0.001	P<0.001	P=0.16
Untreated check (T1)		3867a	4358b	3942	385a	345a	55
Mowing (T2)		1468b	4503b	3621	190b	362a	112
2,4-D (T3)		3964a	5443a	4046	76b	104b	1
2,4-D+mecoprop+dicamba (T4)		3696a	5707a	4133	70b	60b	8
Clopyralid (T5)		3855a	5393a	3989	151b	72b	13
Picloram + 2,4-D (T6)		3714a	5857a	4333	53b	30b	8
SE		185	178	181	41	43	34
Block X Treatment	15	F=1.14	F=0.74	F=0.90	F=2.91	F=3.26	F=0.67
		P=0.34	P=0.77	P=0.54	P<0.01	P<0.001	P=0.74
Block X Rep(Treat) – Error 1	72						
Fertilization	1	F=137.60	F=415.09	F=171.46	F=1.32	F=19.59	F=3.52
		P<0.001	P<0.001	P<0.001	P=0.26	P<0.001	P=0.07
Fertilized (F)		4156	6643	4874	138	101	9
Unfertilized (UF)		2698	3778	3148	171	224	57
SE		88	99	93	20	20	18
Treatment X Fertilization	5	F=1.39	F=1.16	F=1.49	F=0.41	F=7.11	F=1.89
		P=0.24	P=0.34	P=0.21	P=0.84	P<0.001	P=0.11
T1 X F		4730	5617	5109	381	317	51
T1 X UF		3003	3099	2775	390	373	59
T2 X F		1845	6248	4320	149	116b[x]	2b
T2 X UF		1091	2758	2922	232	608a	223a
T3 X F		4811	6878	4702	39	68	0
T3 X UF		3116	4009	3390	112	140	3
T4 X F		4433	7028	5162	52	46	1
T4 X UF		2958	4385	3104	87	74	15
T5 X F		4607	6937	4791	131	46	0
T5 X UF		3102	3849	3187	171	98	26
T6 X F		4511	7149	5157	73	12	1
T6 X UF		2918	4564	3508	32	49	15
SE		215	244	228	50	48	44
Block X Treatment X Fertilization	15	F=1.61	F=1.59	F=0.45	F=0.55	F=2.54	F=0.64
		P=0.09	P=0.10	P=0.91	P=0.90	P<0.01	P=0.78
Residual Error	72						

[z]Means and pooled SEs are calculated for untransformed data. Where applicable, Tukey's test (P<0.05) was used for intra-treatment comparisons. F statistics, P values, and mean comparisons of grass and forb biomass are based on un-transformed data.

[y]Site 3 was lost in 2001, so grass and forb biomass were based on three sites in 2001. Therefore, df were 10 (Block X Treatment, Block X Treatment X Fertilization) and 54 [Block X Rep(Treat), Residual Error].

[x]All interaction mean comparisons are between fertilized and unfertilized treatments within each method of thistle control, within each year. Means with different letters differ, at P<0.05.

Table 4.10 Means and pooled SEs, as well as ANOVA *F* test significance values for grass crude protein content and yield by thistle control treatment, fertilization, and treatment X fertilization combinations, from 4 pastures sites in central Alberta for 1999 to 2001[z].

Source	df	Crude Protein (%)			Crude Protein Yield ($kg \cdot ha^{-1}$)		
		1999[y]	2000[y]	2001	1999[y]	2000[y]	2001
Treatment	5	*F*=1.86	*F*=0.17	*F*=0.11	*F*=0.24	*F*=9.15	*F*=2.02
		P=0.13	*P*=0.95	*P*=0.99	*P*=0.92	*P*<0.001	*P*=0.09
Untreated check (T1)		9.9	10.1	11.7	387	443b	476
Mowing (T2)		n/a	n/a	11.8	n/a	n/a	443
2,4-D (T3)		10.1	9.9	11.7	403	547a	497
2,4-D+mecoprop+dicamba (T4)		10.5	10.0	11.5	392	575a	497
Clopyralid (T5)		9.7	10.1	11.6	381	542a	487
Picloram + 2,4-D (T6)		10.1	10.0	11.7	380	605a	539
SE		0.2	0.2	0.2	19	20	22
Block X Treatment	15	*F*=0.64	*F*=1.35	*F*=0.72	*F*=0.63	*F*=1.46	*F*=1.25
		P=0.80	*P*=0.22	*P*=0.70	*P*=0.81	*P*=0.17	*P*=0.28
Block X Rep(Treat) – Error 1	72						
Fertilization	1	*F*=276.50	*F*=42.42	*F*=195.49	*F*=267.47	*F*=373.32	*F*=390.19
		P<0.001	*P*<0.001	*P*<0.001	*P*<0.001	*P*<0.001	*P*<0.001
Fertilized (F)		11.3	10.6	13.2	516	712	649
Unfertilized (UF)		8.8	9.4	10.1	262	373	331
SE		0.1	0.1	0.2	11	12	11
Treatment X Fertilization	5	*F*=0.79	*F*=0.55	*F*=0.55	*F*=0.31	*F*=0.83	*F*=0.80
		P=0.54	*P*=0.70	*P*=0.74	*P*=0.87	*P*=0.51	*P*=0.56
T1 X F		11.2	10.6	13.1	513	586	662
T1 X UF		8.5	9.7	10.3	262	301	290
T2 X F		n/a	n/a	13.3	n/a	n/a	576
T2 X UF		n/a	n/a	10.2	n/a	n/a	310
T3 X F		11.4	10.5	13.6	539	718	651
T3 X UF		8.8	9.3	9.8	268	376	344
T4 X F		11.9	10.4	12.9	522	748	665
T4 X UF		9.0	9.5	10.2	261	403	330
T5 X F		10.8	10.8	13.1	493	735	648
T5 X UF		8.6	9.4	10.0	270	349	327
T6 X F		11.3	10.8	13.1	513	772	693
T6 X UF		8.9	9.3	10.2	248	438	385
SE		0.2	0.3	0.4	25	28	28
Block X Treatment X Fertilization	15	*F*=0.54	*F*=0.62	*F*=0.82	*F*=1.50	*F*=0.97	*F*=0.72
		P=0.88	*P*=0.82	*P*=0.61	*P*=0.15	*P*=0.49	*P*=0.70
Residual Error	72						

[z]Means and pooled SEs are calculated for untransformed data. Where applicable, Tukey's test ($P<0.05$) was used for intra-treatment comparisons. *F* statistics, *P* values, and mean comparisons of all grass forage quality variables are based on untransformed data.

[y]Mowed plots were not analyzed in 1999 and 2000. Therefore, df were 4 (Treatment, Treatment X Fertilization), 12 (Block X Treatment, Block X Treatment X Fertilization) and 60 [Block X Rep(Treat), Residual Error] in 1999 and 2000. In addition, Site 3 was lost in 2001, so 2001 data is based on 3 sites. Therefore, df were 5 (Treatment, Treatment X Fertilization), 10 (Block X Treatment, Block X Treatment X Fertilization) and 54 [Block X Rep(Treat), Residual Error] in 2001.

Table 4.11 Means and pooled SEs, as well as ANOVA *F* test significance values for grass phosphorus and acid detergent fiber (ADF) content by thistle control treatment, fertilization, and treatment X fertilization combinations, from 4 pastures sites in central Alberta for 1999 to 2001[z].

Source	df	Phosphorus (%)	ADF (%)		
		1999[y]	1999[y]	2000[y]	2001
Treatment	5	$F = 0.76$	$F = 2.01$	$F = 1.07$	$F = 1.13$
		$P = 0.56$	$P = 0.10$	$P = 0.38$	$P = 0.35$
Untreated check (T1)		0.14	37.3	44.1	44.8
Mowing (T2)		n/a	n/a	n/a	43.8
2,4-D (T3)		0.15	36.4	44.3	448
2,4-D+mecoprop+dicamba (T4)		0.15	36.0	43.3	44.5
Clopyralid (T5)		0.14	36.4	44.0	44.1
Picloram + 2,4-D (T6)		0.15	36.4	44.3	44.7
SE		0.01	0.3	0.4	0.4
Block X Treatment	15	$F = 0.71$	$F = 0.75$	$F = 0.62$	$F = 1.28$
		$P = 0.74$	$P = 0.70$	$P = 0.81$	$P = 0.27$
Block X Rep(Treat) – Error 1	72				
Fertilization	1	$F = 71.53$	$F = 0.22$	$F = 40.78$	$F = 4.42$
		$P < 0.001$	$P = 0.64$	$P < 0.001$	$P = 0.04$
Fertilized (F)		0.17	36.5	45.0	44.8
Unfertilized (UF)		0.13	36.5	43.1	44.1
SE		0.003	0.1	0.2	0.3
Treatment X Fertilization	5	$F = 1.98$	$F = 1.27$	$F = 1.35$	$F = 0.57$
		$P = 0.11$	$P = 0.29$	$P = 0.26$	$P = 0.72$
T1 X F		0.17a[x]	37.6	45.2	45.0
T1 X UF		0.11b	37.0	42.9	44.6
T2 X F		n/a	n/a	n/a	44.7
T2 X UF		n/a	n/a	n/a	42.9
T3 X F		0.16a	36.1	45.7	45.2
T3 X UF		0.14b	36.6	42.9	44.3
T4 X F		0.17a	35.7	44.3	44.5
T4 X UF		0.13b	36.3	42.4	44.6
T5 X F		0.16a	36.4	44.4	44.7
T5 X UF		0.12b	36.4	43.7	43.5
T6 X F		0.16a	36.4	45.2	44.9
T6 X UF		0.13b	36.5	43.4	44.5
SE		0.01	0.3	0.5	0.6
Block X Treatment X Fertilization	15	$F = 0.49$	$F = 0.53$	$F = 2.25$	$F = 0.50$
		$P = 0.91$	$P = 0.89$	$P = 0.02$	$P = 0.88$
Residual Error	72				

[z]Means and pooled SEs are calculated for untransformed data. Where applicable, Tukey's test ($P<0.05$) was used for intra-treatment comparisons. *F* statistics, *P* values, and mean comparisons of all grass forage quality variables are based on untransformed data.

[y]Mowed plots were not analyzed in 1999 and 2000. Therefore, df were 4 (Treatment, Treatment X Fertilization), 12 (Block X Treatment, Block X Treatment X Fertilization) and 60 [Block X Rep(Treat), Residual Error] in 1999 and 2000. In addition, Site 3 was lost in 2001, so 2001 data is based on 3 sites. Therefore, df were 5 (Treatment, Treatment X Fertilization), 10 (Block X Treatment, Block X Treatment X Fertilization) and 54 [Block X Rep(Treat), Residual Error] in 2001.

[x]All interaction mean comparisons are between fertilized and unfertilized treatments within each method of thistle control, within each year. Means with different letters differ, at $P<0.05$.

Table 4.12 Means and pooled SEs, as well as ANOVA *F* test significance values for forb crude protein content and yield by thistle control treatment, fertilization, and treatment X fertilization combinations, from 2 pastures sites in central Alberta for 1999 and 2000[z].

Source	df	Crude Protein (%)		Crude Protein Yield ($kg ha^{-1}$)	
		1999[y]	2000	1999[y]	2000
Treatment	5	$F = 12.32$	$F = 3.71$	$F = 11.55$	$F = 5.40$
		$P < 0.001$	$P < 0.01$	$P < 0.001$	$P < 0.001$
Untreated check (T1)		14.8a	14.0a	94a	56a
Mowing (T2)		n/a	13.1ab	n/a	44ab
2,4-D (T3)		12.7b	12.5b	17b	21abc
2,4-D+mecoprop+dicamba (T4)		10.8bc	12.7b	13b	6bc
Clopyralid (T5)		12.2bc	12.6b	29b	7bc
Picloram + 2,4-D (T6)		10.6c	13.0ab	10b	2c
SE		0.5	0.3	10	10
Block X Treatment	5	$F = 3.89$	$F = 0.29$	$F = 0.48$	$F = 4.18$
		$P = 0.01$	$P = 0.91$	$P = 0.75$	$P < 0.01$
Block X Rep(Treat) – Error 1	36				
Fertilization	1	$F = 0.31$	$F = 7.65$	$F = 0.13$	$F = 0.59$
		$P = 0.58$	$P < 0.01$	$P = 0.72$	$P = 0.45$
Fertilized (F)		12.2	12.7	31	20
Unfertilized (UF)		12.3	13.3	34	25
SE		0.18	0.13	5	5
Treatment X Fertilization	5	$F = 5.64$	$F = 15.40$	$F = 0.50$	$F = 2.76$
		$P < 0.01$	$P < 0.001$	$P = 0.74$	$P = 0.03$
T1 X F		15.0	14.5a	96	75a
T1 X UF		14.7	13.5b	91	37b
T2 X F		n/a	12.0b	n/a	16b
T2 X UF		n/a	14.2a	n/a	71a
T3 X F		11.7b[x]	12.3	8	16
T3 X UF		13.6a	12.7	25	26
T4 X F		10.6	11.2b	8	3
T4 X UF		11.1	14.1a	18	9
T5 X F		12.0	13.6a	27	7
T5 X UF		12.4	11.7b	30	7
T6 X F		11.5a	12.7	16	2
T6 X UF		9.7b	13.4	4	2
SE		0.4	0.3	11	13
Block X Treatment X Fertilization	5	$F = 0.14$	$F = 1.56$	$F = 0.44$	$F = 0.85$
		$P = 0.97$	$P = 0.20$	$P = 0.78$	$P = 0.52$
Residual Error	36				

[z]Data were from pasture sites 3 and 4. Means and pooled SEs are calculated for untransformed data. Where applicable, Tukey's test ($P<0.05$) was used for intra-treatment comparisons. *F* statistics, *P* values, and mean comparisons of all forb forage quality variables are based on untransformed data.

[y]Mowed plots were not analyzed in 1999. Therefore, df were 4 (Treatment, Treatment X Fertilization, Block X Treatment, Block X Treatment X Fertilization) and 30 [Block X Rep(Treat), Residual Error] in 1999.

[x]All interaction mean comparisons are between fertilized and unfertilized treatments within each method of thistle control, within each year. Means with different letters differ, at $P<0.05$.

Table 4.13 Means and pooled SEs, as well as ANOVA *F* test significance values for forb phosphorus and acid detergent fiber (ADF) content by thistle control treatment, fertilization, and treatment X fertilization combinations, from 2 pastures sites in central Alberta for 1999 and 2000[z].

Source	df	Phosphorus (%)	ADF (%)	
		1999[y]	1999[y]	2000
Treatment	5	*F* = 1.00	*F*=0.15	*F*=18.47
		P = 0.42	*P*=0.96	*P*<0.001
Untreated check (T1)		0.20	32.4	35.9a
Mowing (T2)		n/a	n/a	35.9a
2,4-D (T3)		0.23	32.0	32.7b
2,4-D+mecoprop+dicamba (T4)		0.20	32.5	33.3b
Clopyralid (T5)		0.20	31.6	34.1ab
Picloram + 2,4-D (T6)		0.23	33.0	30.6c
SE		0.02	1.3	0.5
Block X Treatment	5	*F* = 1.30	*F*=3.24	*F*=0.41
		P = 0.29	*P*=0.03	*P*=0.84
Block X Rep(Treat) – Error 1	36			
Fertilization	1	*F* = 1.52	*F*=13.13	*F*=19.53
		P = 0.23	*P*<0.01	*P*<0.001
Fertilized (F)		0.22	33.7	34.5
Unfertilized (UF)		0.21	30.9	33.0
SE		0.01	0.53	0.24
Treatment X Fertilization	5	*F* = 0.97	*F*=0.73	*F*=11.10
		P = 0.44	*P*=0.58	*P*<0.001
T1 X F		0.22	33.3	37.2a[x]
T1 X UF		0.19	31.5	34.6b
T2 X F		n/a	n/a	37.9a
T2 X UF		n/a	n/a	34.0b
T3 X F		0.22	34.4	33.8a
T3 X UF		0.23	29.7	31.6b
T4 X F		0.20	33.1	35.2a
T4 X UF		0.19	31.9	31.4b
T5 X F		0.21	32.7	33.8
T5 X UF		0.19	30.4	34.3
T6 X F		0.23	34.8	29.1b
T6 X UF		0.24	31.1	32.1a
SE		0.01	1.2	0.6
Block X Treatment X Fertilization	5	*F* = 2.26	*F*=0.09	*F*=2.61
		P = 0.09	*P*=0.99	*P*=0.04
Residual Error	36			

[z]Data were from pasture sites 3 and 4. Means and pooled SEs are calculated for untransformed data. Where applicable, Tukey's test ($P<0.05$) was used for intra-treatment comparisons. *F* statistics, *P* values, and mean comparisons of all forb forage quality variables are based on untransformed data.

[y]Mowed plots were not analyzed in 1999. Therefore, df were 4 (Treatment, Treatment X Fertilization, Block X Treatment, Block X Treatment X Fertilization) and 30 [Block X Rep(Treat), Residual Error] in 1999.

[x]All interaction mean comparisons are between fertilized and unfertilized treatments within each method of thistle control, within each year. Means with different letters differ, at $P<0.05$.

Table 4.14 Means and pooled SEs, as well as ANOVA *F* test significance values for species richness and diversity by thistle control treatment, fertilization, and treatment X fertilization combinations, from 4 pastures sites in central Alberta for 1999 to 2001[z].

Source	df	Richness (no of species per m^2)			Diversity Index (per m^2)		
		1999	2000	2001	1999	2000	2001
Treatment	5	F=5.96	F=9.88	F=2.26	F=3.97	F=12.82	F=1.27
		P<0.001	P<0.001	P=0.06	P<0.01	P<0.001	P=0.29
Untreated check (T1)		7a	6a	4	1.18a	1.03a	0.69
Mowing (T2)		5b	6a	4	1.08ab	1.05a	0.64
2,4-D (T3)		5b	4b	3	0.95bc	0.77b	0.55
2,4-D+mecoprop+dicamba (T4)		5b	4b	3	0.99bc	0.82b	0.62
Clopyralid (T5)		6ab	5ab	3	0.96bc	0.83b	0.58
Picloram + 2,4-D (T6)		5b	4b	3	0.88c	0.73b	0.58
	SE	0.2	0.3	0.2	0.04	0.04	0.05
Block X Treatment	15	F=1.31	F=1.35	F=0.96	F=1.49	F=0.72	F=0.71
		P=0.22	P=0.19	P=0.51	P=0.13	P=0.76	P=0.77
Block X Rep(Treat) – Error 1	72						
Fertilization	1	F=6.72	F=32.71	F=44.53	F=7.55	F=77.42	F=17.22
		P=0.01	P<0.001	P<0.001	P<0.01	P<0.001	P<0.001
Fertilized (F)		5	4	3	0.98	0.77	0.55
Unfertilized (UF)		6	5	4	1.03	0.97	0.67
	SE	0.1	0.1	0.1	0.02	0.02	0.02
Treatment X Fertilization	5	F=0.68	F=0.65	F=1.35	F=1.90	F=2.40	F=0.90
		P=0.64	P=0.67	P=0.25	P=0.11	P=0.05	P=0.49
T1 X F		7	5	3	1.12	0.96b[y]	0.57
T1 X UF		7	6	4	1.24	1.11a	0.80
T2 X F		5	5	3	1.11	0.86b	0.58
T2 X UF		6	7	4	1.05	1.24a	0.71
T3 X F		5	4	3	0.87	0.68b	0.53
T3 X UF		6	4	3	1.02	0.86a	0.57
T4 X F		5	4	3	0.96	0.70b	0.58
T4 X UF		6	5	4	1.02	0.94a	0.66
T5 X F		6	4	3	0.92	0.74b	0.53
T5 X UF		6	6	3	1.00	0.92a	0.62
T6 X F		5	4	3	0.89	0.66b	0.49
T6 X UF		5	4	4	0.87	0.79a	0.67
	SE	0.3	0.3	0.2	0.05	0.04	0.05
Block X Treatment X Fertilization	15	F=1.60	F=0.72	F=1.66	F=0.94	F=1.32	F=0.94
		P=0.09	P=0.75	P=0.08	P=0.52	P=0.22	P=0.53
Residual Error	72						

[z] Means and pooled SEs are calculated for untransformed data. Where applicable, Tukey's test (P<0.05) was used for intra-treatment comparisons. F statistics, P values, and mean comparisons of species richness and diversity are based on untransformed data, with the exception of diversity in 1999, which was log(X+1) transformed prior to analysis.

[y] All interaction mean comparisons are between fertilized and unfertilized treatments within each method of thistle control, within each year. Means with different letters differ, at P<0.05.

Table 4.15 Means and pooled SEs, as well as ANOVA *F* test significance values for native species and legume cover by thistle control treatment, fertilization, and treatment X fertilization combinations, from 3 pastures sites in central Alberta for 1999 to 2001[z].

Source	df	Native Species Cover (%)[y]			Legume Cover (%)[x]		
		1999	2000	2001	1999	2000	2001
Treatment	5	*F*=4.16	*F*=3.28	*F*=2.32	*F*=16.28	*F*=9.34	*F*=1.41
		P<0.01	*P*=0.01	*P*=0.06	*P*<0.001	*P*<0.001	*P*=0.25
Untreated check (T1)		9a	8a	3	22a	13ab	0.8
2,4-D (T3)		1b	0b	0	4b	3bc	0.3
2,4-D+mecoprop+dicamba (T4)		2b	2ab	2	3b	0.3bc	0.2
Clopyralid (T5)		1b	1b	0	4b	0.03c	0.2
Picloram + 2,4-D (T6)		1b	1b	0	1b	0c	0
SE		1.5	1.5	0.7	2.5	2.9	1.0
Block X Treatment	15	*F*=0.51	*F*=0.38	*F*=0.23	*F*=0.72	*F*=0.82	*F*=0.57
		P=0.87	*P*=0.95	*P*=0.99	*P*=0.61	*P*=0.54	*P*=0.72
Block X Rep(Treat) – Error 1	54						
Fertilization	1	*F*=1.91	*F*=1.43	*F*=0.53	*F*=9.02	*F*=22.39	*F*=0.01
		P=0.17	*P*=0.24	*P*=0.47	*P*<0.01	*P*<0.001	*P*=0.94
Fertilized (F)		2	2	1	7	2	0.8
Unfertilized (UF)		3	3	1	13	10	0.7
SE		0.5	0.9	0.3	1.3	1.2	0.15
Treatment X Fertilization	5	*F*=0.10	*F*=0.21	*F*=0.04	*F*=2.60	*F*=12.61	*F*=0.22
		P=0.99	*P*=0.96	*P*=0.99	*P*=0.04	*P*<0.001	*P*=0.95
T1 X F		8	8	2	17b[w]	10.8	1.0
T1 X UF		9	8	3	27a	14.5	0.6
T2 X F		1	1	0	14b	2.6b	2.9
T2 X UF		1	4	0	32a	40.5a	3.1
T3 X F		1	0	0	2	0.1	0.3
T3 X UF		1	0	0	6	6.2	0.3
T4 X F		1	0	1	3	0	0.1
T4 X UF		2	4	2	4	0.6	0.3
T5 X F		1	0	0	3	0.1	0.3
T5 X UF		2	1	0	5	0.1	0.1
T6 X F		1	0	0	2	0	0
T6 X UF		2	1	1	0	0	0.1
SE		1.1	2.2	0.8	3.2	2.9	0.4
Block X Treatment X Fertilization	10	*F*=1.36	*F*=1.55	*F*=1.42	*F*=1.41	*F*=2.76	*F*=3.33
		P=0.23	*P*=0.15	*P*=0.20	*P*=0.24	*P*=0.03	*P*=0.01
Residual Error	54						

[z]Means and pooled SEs are calculated for untransformed data. Where applicable, Tukey's test ($P<0.05$) was used for intra-treatment comparisons. *F* statistics, *P* values, and mean comparisons of native and legume species cover are based on untransformed data.

[y]As a result of the lack of native species at Site 1 (Barrhead), this site was left out of the analysis for native species.

[x]Sites 1 and 2 did not contain any legumes, so only Sites 3 and 4 were analyzed for legume cover. Therefore, df were 5 (Treatment, Treatment X Fertilization, Block X Treatment, Block X Treatment X Fertilization) and 36 [Block X Rep(Treat), Residual Error] for legume cover.

[w]All interaction mean comparisons are between fertilized and unfertilized treatments within each method of thistle control, within each year. Means with different letters differ, at $P<0.05$.

5. SPONGE WIPER APPLICATION OF HERBICIDES FOR CANADA THISTLE CONTROL IN PASTURES

5.1 Introduction

Canada thistle [*Cirsium arvense* (L.) Scop.] is a serious agricultural weed found on cultivated, pasture, and hay land across Canada and the northern United States (Moore 1975; Donald 1990; Skinner et al. 2000). Estimates indicated that as many as 9 million acres (4 M. ha) were infested in the 1960's in Alberta (Alex 1966). More recently, Canada thistle was reported in 53% of all Alberta cereal and oilseed fields surveyed in 1997 (Thomas et al. 1998). The few weed surveys of forage crops available in western Canada suggest Canada thistle is a problem in pasture and hayland (Thomas and Wise 1983), as well as alfalfa (*Medicago sativa* L.) seed fields (Goodwin et al. 1986). The most effective methods of thistle control in forages include mowing at the early bud stage to deplete root carbohydrate reserves, and spraying with MCPA, 2,4-D, picloram, dicamba, or clopyralid (Moore 1975; Gallagher and Vanden Born 1976; Amor and Harris 1977; Peterson and Parochetti 1978; Haggar et al. 1986; Donald 1990).

While broadcast spraying is effective for weed control, there are problems associated with this procedure, including herbicide drift, damage to desirable forages, and increased costs of treating large areas with low weed densities. Wiper applicators are an alternative weed control option that may reduce these problems, as wipers selectively apply chemical to weeds taller than the forage crop (Wyse and Habstritt 1977; Moomaw and Martin 1990).

Most weed wiping research to date has focused on brush control (e.g., Mayeux and Crane 1983, 1984; Gibson et al. 1984; Mayeux 1987; Bovey and Meyer 1989). In northeastern Saskatchewan, a carpeted roller applicator was used to control aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), and willow (*Salix* spp.) regrowth, with 2,4-D + picloram at 0.60 + 0.07% a.i., and glyphosate at 0.53% a.i., providing better control than 2,4-D at 0.25 to 6.75% a.i. (Waddington and Bittman 1987a). In the United States, a number of studies have also looked at the use of wipers for herbaceous weed control, including dandelion (*Taraxacum officinale* Web.), buckhorn plantain (*Plantago lanceolata* L.; e.g., Welker and Peterson 1989), and leafy spurge, *Euphorbia esula* L. (e.g., Messersmith and Lym 1985; Moomaw and Martin 1985, 1990). Specific results of these studies vary, but generally support the utility of wipers for weed control. Wipers reduce herbicide drift while maintaining weed control equivalent to a spray applicator (Welker and Peterson 1989). Selective applicators apply as little as 40% of the herbicide used in spray applications (Messersmith and Lym 1985).

Foliar, broadcast spray applications of the systemic herbicides glyphosate, dicamba, clopyralid, and picloram control Canada thistle, while phenoxy herbicides such as 2,4-D, and MCPA are less effective (Amor and Harris 1977; Reece and Wilson 1983; Donald 1990). In birdsfoot trefoil (*Lotus corniculatus* L.) seed fields in Minnesota, comparisons of 10 and 33% (v/v) solutions of commercial herbicide formulations showed picloram, clopyralid, and glyphosate controlled Canada thistle better than MCPA and dicamba, but picloram, clopyralid, and dicamba injured trefoil, while glyphosate and MCPA did not (Boerboom and Wyse 1988a). In Montana, Krueger-Mangold et al.

(2002) found that wick-applied glyphosate controlled Canada thistle in riparian areas important for waterfowl production.

Where there is adequate height separation between thistle and the forage stand in grazed swards, the application of glyphosate with a weed wiper may control Canada thistle and retain shorter plants that are herbicide susceptible. Because glyphosate is both non-selective and systemic, the survival of taller grasses and desirable forbs that grow inter-mixed with thistles may be compromised with wiper use. As a result, the benefits of wiping with a non-selective herbicide under these conditions may be offset by damage to desirable vegetation. In comparison, wiping with selective herbicides such as dicamba, clopyralid, and picloram may maintain greater grass production. Nevertheless, wiper-application of these herbicides may not reduce chemical residues in the soil. For example, roller applied picloram on leafy spurge resulted in similar picloram residues to those on broadcast sprayed areas (Messersmith and Lym 1985). While picloram persistence may prolong weed control, it may also inhibit the subsequent growth of desirable legumes (Hickman et al. 1989).

Presently, no published data exist on the effectiveness of a sponge weed-wiper for controlling Canada thistle in pastures of western Canada, and no studies have apparently assessed the use of selective herbicides. Consequently, two field experiments were conducted in pastures to investigate the impacts of wiper-applied herbicides on thistle abundance and pasture forage production and composition. The objective of the initial experiment was to evaluate the effects of sponge wiper-applied glyphosate on Canada thistle abundance and herbage production. A second experiment compared levels of

Canada thistle control and subsequent forage sward response from sponge wiper-applied, selective broad-leaf herbicides to that of glyphosate.

5.2 Materials and Methods

5.2.1 Study Sites

The two experiments were conducted in pastures situated throughout the Aspen Parkland of central Alberta from 1999 to 2001 (Experiment 1), and 2000 to 2002 (Experiment 2). The first experiment was carried out at 4 pasture sites, and the second at 3 (Table 5.1; Appendix 1.3). Each site met the following criteria: (1) they were relatively uniform in both physical conditions (e.g., soils and disturbance history) and forage sward composition, (2) they had a heavy infestation of Canada thistle (e.g., > 10 shoots m^{-2}), (3) they were relatively free of other noxious weeds, and (4) they had not been sprayed for at least 3 years prior to 1999. All sites were tame pastures dominated by some combination of the following grass species: smooth brome (*Bromus inermis* Leyss.), Kentucky bluegrass (*Poa pratensis* L.), and quackgrass (*Agropyron repens* (L.) Beauv.) (Table 5.1). Dominant forb species included dandelion, (*Taraxacum officinale* Web.), white clover (*Trifolium repens* L.), and alsike clover (*Trifolium hybridum* L.). Additionally, pastures selected for Experiment 2 had a minimum initial clover (*Trifolium* spp.) cover of 10%.

At each site, treatments were carried out in an unfenced area approximately 15 by 30 m (Experiment 1) and 10 by 70 m (Experiment 2). Grazing by cattle was done prior to herbicide application to facilitate adequate height separation between the thistle and

forage stand. Stocking rates were typical of the historical grazing regime for each pasture based on the resident commercial livestock operation.

Soil texture (hand-texturing) and soil type were determined at all sites (Table 5.1), but more detailed soils data were collected for the 3 pastures of the second experiment (Table 5.2). At these sites in August of 2001, soils were sub-sampled at four points randomly distributed throughout each of the four, check plots, and then pooled prior to lab analysis. Two depths were sampled (0-15 and 15-30 cm), with each depth analyzed separately, and the results of the two averaged following analysis. Analyses of nitrogen (nitrate), phosphorus (phosphate), and potassium were conducted according to the methods of Ashworth and Mrazek (1995), while sulfur (sulfate), organic matter, pH, electrical conductivity, and particle size were determined using the methods of McKeague (1978). At these sites, soil pH, E.C., and organic matter ranged from 6.6 to 7.3, 0.33 to 0.62 $dS \cdot cm^{-1}$, and 9.3 to 14.6%, respectively. Lab analysis of soil macronutrients found that all 3 sites were deficient in nitrogen, and generally low in P, K, and S (Table 5.2).

Regional precipitation data were collected for all years of the study (Table 5.3).

5.2.2 Experimental Design

The initial experiment was set up as a split-plot, randomized complete block design, with timing of wiper application as the whole plot factor, and a one-time, wiping treatment in 1999 as the sub-plot factor. There were two application timings, (1) late bud, and (2) fluff stage of Canada thistle growth, with two sites treated at each time. Treatments included wiper-applied glyphosate applied at the label recommendation of

33% solution (117 g a.i. L^{-1}), wiped in two directions, and an untreated check. Application timings were randomly assigned to sites, with the Barrhead and Lamont sites treated when the majority of Canada thistle plants were at the late bud stage (27 July), while the Spruce Grove and Thorsby sites were treated when the majority of thistle plants were at the flowering/early fluff stage (20 August and 1 September, respectively). Wiped and check plots were each 3.5 by 15 m in size, and replicated 4 times at each site.

The wiper applicator was a hand-pushed, gravity-fed, 11 foot (3.4m) sponge weed wiper made by Smucker Manufacturing Inc. The wiper height was set at 30 cm for Barrhead and Lamont, and 35 cm for Spruce Grove and Thorsby. Wiping was carried out bi-directionally, using saturated sponges (i.e., when the sponges had just started to drip). At the time of wiping, thistles ranged in height from 10 to 120 cm, while grazed herbage between patches of thistle was generally 10 – 15 cm high.

The second field experiment was established in 2000 as a randomized complete block design, with five treatments replicated four times at each of three blocks (pasture sites). Treatments included an untreated check and wiped plots of glyphosate, 2,4-D+mecoprop+dicamba, clopyralid, and picloram+2,4-D. At the time of the study, label recommendations for herbicide concentration during wiper application were only available for glyphosate (33% v/v of the commercial formulation). As a result, the other herbicide concentrations were determined by equating the commercial retail cost of the three selective broadleaf herbicides tested with that of a 33% glyphosate solution. This was done for a number of reasons. First, a comparison of equal amounts of active ingredient would have resulted in several treatments being uneconomical and impractical. Second, at fixed concentrations, different herbicides would likely have vastly different

potencies associated with their active ingredient. Finally, this method (i.e., cost equivalency) kept results relevant to the decision-making process used by livestock producers. The resulting herbicide wiper rates used, based on v/v solutions of the commercial formulations, were: (1) 33% glyphosate (117 g a.i. L^{-1}), (2) 24% 2,4-D + mecoprop + dicamba (71 + 19 + 26 g a.i. L^{-1}), (3) 2% clopyralid (7 g a.i. L^{-1}), and (4) 20% picloram + 2,4-D (13 + 48 g a.i. L^{-1}). All herbicide treatments were one-time applications.

At each site, treatments were randomly assigned to plots 3.5 by 10 m in size, and all herbicides applied bi-directionally with the same Smucker, sponge weed-wiper used in the first trial. Wiping was carried out at the Morinville, Edmonton, and Wetaskiwin pasture sites on August 3, 4, and 15, 2000, respectively. At the time of wiping, Canada thistle was at the early flowering stage (approximately 15 to 30% thistle stems flowering), and ranged in height from 10 to 150 cm. Herbage ranged in height from 5 to 90 cm, with the majority of grass, dandelion, and clover plants at 15, 10, and 10 cm height, respectively.

The sponge wiper was set at a height of 30 to 40 cm, which allowed contact with the majority of thistle stems while ensuring clearance of the grazed herbage between thistle stems. Separate sponges were used for each herbicide, and the wiper herbicide delivery system thoroughly flushed with distilled water between herbicides.

5.2.3 Vegetation Sampling

Plots were not fenced for either experiment, with cattle permitted to graze the pastures throughout each experiment. However, in the two years after application (2000,

2001 for the glyphosate experiment, and 2001, 2002 for the multiple herbicides experiment), range cages were used to prevent cattle from grazing the plots. This was done to ensure that residual thistle and forage biomass measured was not affected by grazing in the year of sampling.

5.2.3.1 Glyphosate Experiment

Approximately 3 to 4 weeks following wiping in 1999, plots were sampled for live and dead thistle shoot densities using 4, 0.5 m^2 quadrats within each plot. Barrhead and Lamont sites were sampled on August 19 and 20, respectively, while both Spruce Grove and Thorsby were sampled on September 22.

In early May 2000, prior to cattle grazing, two range cages (1.5 by 1.5 m in size) were set out in each plot to exclude cattle. At peak standing biomass in late July of 2000, residual live thistle shoot densities were determined in four, 0.5 m^2 quadrats within each plot (two inside cages, two outside cages), while herbage (separated into grass and forb) and thistle shoot biomass were sampled to ground level in one, 0.5 m^2 quadrat within each range cage. All harvested samples were oven-dried at 60°C to constant mass, and weighed. Range cages were removed following sampling to permit cattle grazing in order to prevent excess litter accumulation and maintain active pasture use.

Range cages were again set out in all plots in spring 2001. At peak vegetation growth in mid to late July, thistle and herbage were again sampled using the same procedure as the previous year at all sites except Spruce Grove, which was accidentally ploughed by the landowner, removing it from the trial. Because of the large amount of

annual forbs that appeared in some plots during 2000, forbs were separated into annuals and perennials in 2001.

5.2.3.2 Multiple Herbicides Experiment

One day prior to wiping at each site in August of 2000, pre-treatment, live thistle shoot densities were measured in 4, 0.5 m^2 permanent quadrats within each plot. Post-treatment live thistle densities were measured in the same quadrats on 10 September at Wetaskiwin, and on 27 September at Edmonton and Morinville.

Prior to grazing in May 2001, 1.5 by 1.5 m range cages (two per plot) were set out at each site to exclude cattle. At peak standing biomass in mid-August 2001, live thistle shoot density was sampled in 4, 0.5 m^2 quadrats randomly placed within each plot (two inside cages, two outside cages). In addition, thistle, grass, and forb biomass in a 0.5 m^2 quadrat within each range cage were harvested to a 2 cm height. Forbs were further separated into annuals and perennials to assess the residual impacts of wiping on these components. Ocular estimates (% canopy cover) of species composition were also made within each plot. All harvested samples were oven-dried at 60°C to constant mass, and weighed.

In spring 2002, range cages were again set out in all plots at each site except the Morinville site, which was ploughed by the landowner in the spring, removing it from the trial. Thistle and herbage were again sampled at peak vegetation growth in mid to late July, using similar procedures as the previous year, with the exception that smaller (0.25 m^2) quadrats were used, and herbage biomass was not separated into grass and forbs (because of the low overall forb biomass due to severe drought). Cover estimates of

legumes (Edmonton site) and dandelion (Wetaskiwin site) were also determined. Due to the dry conditions and corresponding negligible clover growth at Wetaskiwin in 2002, legume estimates were not determined.

5.2.4 Analysis

Prior to analysis, all data from both experiments were checked for normality through examination of the residuals and tests of the Shapiro–Wilks' statistic (SAS Institute Inc. 1988). In the first experiment (glyphosate), forb biomass was square-root transformed and in the second experiment (multiple herbicides), thistle density and biomass were log(Y+1) transformed prior to analysis. Post-hoc mean comparisons were performed on all significant treatments, based on the F test results ($P < 0.05$) using Tukey's method ($P < 0.05$) (Zar 1996; Steel et al. 1997).

5.2.4.1 Glyphosate Experiment

All data were analyzed using a split-plot analysis of variance (ANOVA) to evaluate the effects of timing of treatment (whole plot), glyphosate wiping, as well as the timing by wiping interaction. Repeated measures ANOVA was not used to test for a year effect because of the change in method used to evaluate forb production, as well as the discontinuity in data arising from loss of the Spruce Grove site in 2001. In addition, precipitation was markedly lower in 2001 than previous years, which visibly resulted in less thistle and herbage production. Data for each year were therefore analyzed separately. Although sites were generally pooled for analyses, initial site by wiping

treatment tests were significant ($P < 0.10$) for some variables. Consequently, results from individual sites are also presented.

Thistle variables analyzed in 1999 included live Canada thistle shoot density and thistle mortality, i.e., % thistle mortality =

$$\frac{\text{no. dead thistle shoots}}{\text{total no. thistle shoots (live + dead)}} \text{ X } 100.$$

ANPP (above-ground, annual net primary production) variables analyzed in 2000 and 2001 were live thistle shoot density and biomass, as well as grass and forb biomass. In 2001, annual and perennial forb biomass were analyzed separately.

5.2.4.2 Multiple Herbicides Experiment

All data were analyzed using ANOVA to evaluate herbicide treatment effects, with analyses performed separately for each year to detect initial (2000) and residual (2001 and 2002) effects. Block by treatment tests indicated no significant site effects ($P > 0.10$) on most variables except legume cover in 2001. As a result, the analyses were carried out across sites. Thistle variables analyzed in 2000 were live Canada thistle shoot density and thistle mortality, i.e.,

$$\text{\% thistle mortality} = \frac{\text{no. pre-treatment live thistle shoots} - \text{no. post-treatment live thistle shoots}}{\text{no. pre-treatment live thistle shoots}} \text{ X } 100.$$

Thistle variables analyzed from 2001 and 2002 were live shoot density and biomass, while the herbage ANPP variables analyzed were grass, annual forb, and perennial forb biomass in 2001, and total herbage biomass (grass+forb) in 2002. In addition, legume

cover was analyzed in 2001 (across all sites), and only at Edmonton in 2002. Dandelion cover was also analyzed at Wetaskiwin in 2002.

5.3 Results and Discussion

5.3.1 Effects of Wiper-Applied Glyphosate

5.3.1.1 Canada Thistle Control

Wiping with glyphosate in 1999 significantly affected ($P<0.01$) all thistle variables in 1999, 2000, and 2001, except biomass in 2001 (Table 5.4), leading to increased thistle mortality in 1999, and decreased live thistle density in all three years of the study. Thistle biomass remained lower in wiper-applied glyphosate plots in both 2000 and 2001, although in 2001, this difference was not significant ($P=0.11$; Table 5.4). Observed reductions in thistle are in agreement with Boerboom and Wyse (1988a), who found that 33% glyphosate applied bi-directionally to Canada thistle at the late bud to early bloom stage with a ropewick in birdsfoot trefoil in Minnesota resulted in significantly greater control of Canada thistle than the untreated check 30 and 400 days after treatment (DAT). In that study, thistle reductions averaged 76% 30 DAT, and were 83 and 38% at 400 DAT for two experiments initiated in 1984 and 1985, respectively (Boerboom and Wyse 1988a). The greater long-term reductions in the 1984 experiment were attributed to low soil moisture in the late summer and fall of that year, which were thought to have limited weed re-establishment (Boerboom and Wyse 1988a). However, only visual thistle control (not shoot density or biomass) was reported, and longer-term responses (i.e., two years or more after treatment) were not determined. More recently,

Krueger-Mangold et al. (2002) in Montana found that wick-applied glyphosate at 1.5, 3.0, and 4.5 kg ai·ha^{-1} applied annually for two consecutive years in a smooth brome sward significantly reduced Canada thistle density and biomass compared to the untreated check. In contrast, the present study found a significant (P<0.05) reduction in Canada thistle density two years after a one-time glyphosate treatment (Table 5.4). Given the growing conditions of the present study, repeated wiper applications of glyphosate may not be necessary to provide longer-term control of Canada thistle in forages.

Although a change in the timing of wiping resulted in no significant differences, timing did interact with wiping to significantly affect thistle mortality and density in 1999, as well as residual thistle biomass in 2000 (P<0.05). Wiping at the late bud stage of Canada thistle growth (July) resulted in significantly greater thistle mortality and lower thistle density than wiping at the fluff stage (August; Table 5.4).

In order to achieve control of perennial weeds such as Canada thistle with foliar-applied glyphosate, translocation of the herbicide into the root and up-take by root buds in toxic amounts must occur (Carlson and Donald 1988; Hunter 1995). Hunter (1995, 1996) found that glyphosate applied at an earlier growth stage (i.e., rosette) resulted in greater thistle control than at later stages (i.e., bud), likely because of progressively less translocation to roots with increased maturity. The explanation for this was that active meristems in the shoot during elongation or flower bud initiation may hinder translocation to the roots (Hunter 1996).

Differences in herbicide translocation may partially explain the greater reductions in thistle that occurred with wiping in July versus August. That is, stem elongation and

bud development may have been greater in August. Additionally, some thistle at the fluff stage in August likely had begun to senesce, which could have resulted in even further reductions in translocation. The significant treatment interaction for thistle density in 1999 and 2000 may also have been partly due to differences in thistle abundance among the two sites wiped at the early bud stage. In particular, the thistle density at Barrhead (72 shoots·m^{-2}; Table 5.1) was markedly greater than all other sites and may have increased the likelihood of a treatment response. This was particularly apparent in 2000, at which time thistle biomass remained lower (P<0.05) as a result of wiping at the Barrhead site only (Table 5.4).

Within check plots, the decrease in thistle density from 41 shoots·m^{-2} in 1999, to 14 shoots·m^{-2} in 2001, and the decrease in thistle biomass from 794 kg·ha^{-1} in 2000, to 136 kg·ha^{-1} in 2001, was likely a result of drought effects experienced in 2001 (Tables 5.3, 5.4). Precipitation in the spring and early summer of 2001 was low compared to previous years. While more substantial precipitation events in the form of thunderstorms occurred in late July and early to mid-August of 2001, low precipitation had likely already impeded thistle growth by the time of vegetation sampling. According to Moore (1975), Canada thistle is particularly sensitive to the warm, dry conditions that accompany drought, and will often demonstrate reduced growth during periods of low precipitation.

5.3.1.2 Effects on Forage Production

Wiping with glyphosate had significant (P<0.05) effects on grass and forb biomass in 2000 only (Table 5.5), with wiped plots lower in grass biomass, but greater in

forb biomass ($P<0.05$). When wiper treatments were applied in 1999, grass plants at all sites had grown intertwined with Canada thistle, such that it was impossible to avoid incidental contact between grass plants and the wiper. As a result, substantial grass kill occurred, which was subsequently reflected in the lower grass production in 2000 (2131 versus 2874 $kg \cdot ha^{-1}$ on wiped and check plots, respectively; Table 5.5).

In contrast, Waddington and Bittman (1987a,b) reported negligible effects on grasses from roller-applied glyphosate for brush control in northeastern Saskatchewan; however, forage yields were not measured. Krueger-Mangold et al. (2002) found that while wick-applied glyphosate for Canada thistle control in the spring did not reduce grass biomass (smooth brome), summer and fall applications did decrease grass biomass compared to the untreated check. These more recent findings are in agreement with the present study.

The systemic nature of glyphosate likely contributed to the grass damage, in part because the dominant grasses present (e.g., smooth brome, quackgrass, and Kentucky bluegrass) are rhizomatous. Translocated glyphosate visibly killed not only the contacted grass stem, but interconnected surrounding stems as well. This was apparent in 2000 as localized "dead" patches of grass, 10-50 cm in size, which were typically associated with dense thistle patches that harbored taller grass stems at the time of wiping. Grasses had begun to recover by 2001, as reflected in the non-significant ($P=0.58$) difference in grass biomass between wiped and check plots in that year (Table 5.5).

The dramatic increase in forb production in 2000 was a result of the invasion of annual, weedy species, including flixweed (*Descurainia sophia* (L.) Webb.), wild buckwheat (*Polygonum convolvulus* L.), stinkweed (*Thlaspi arvense* L.), lamb's-quarters

(*Chenopodium album* L.), ball mustard [*Neslia paniculata* (L.) Desv.], wild mustard [*Brassica kaber* (DC.) L.C. Wheeler], and shepherd's-purse [*Capsella bursa-pastoris* (L.) Medic.]. Competitive release has been defined as "the expansion of the niche of a species associated with the lack of competition with other species" (Begon et al. 1990). Vegetation succession in pastures following disturbances from burrowing animals, livestock, and machines has been linked to the competitive release of species with viable seeds in the soil seed bank (e.g., Begon et al. 1990; Willms and Quinton 1995).

For example, reductions in litter and the creation of bare ground caused by the heavy-grazing of pastures has been shown to increase soil temperature fluctuations, evaporation, and light at the soil surface, all of which influence the dormancy and germination of seeds (Roberts 1986). In southern Alberta, annual, introduced forbs (including shepherd's-purse, lamb's-quarters, and stinkweed) were shown to comprise a large portion of the viable seed bank in soils under both ungrazed and grazed rough fescue (*Festuca campestris* Rydb.) grassland (Willms and Quinton 1995). Soil disturbance caused by heavy grazing in that study led to a seral community dominated by annual forbs rather than rough fescue, as germination of forbs was thought to have occurred as a result of increased soil temperatures and greater exposure to light following removal of litter and creation of bare ground (Willms and Quinton 1995). In a southern Alberta timothy pasture, Johnston et al. (1969) reported as many as 979 viable stinkweed seeds per m^{-2} and also found an increase in annual weeds with increased grazing pressure. Archibald (1981) also reported viable seeds of shepherd's-purse and lamb's-quarters under native prairie and grazed pasture in south-central Saskatchewan. Tracy and Sanderson (2000) reported that of all germinable seeds collected in the top 10 cm of soil

from pastures in the northeast United States, most were from annual and perennial forbs (40 and 23%, respectively), while perennial grasses and legumes made up a smaller proportion (11 and 19%, respectively). Germination tests on seeds from the soils sampled resulted in wild buckwheat, shepherd's-purse, and lamb's-quarters seedling densities of 6, 96, and 319 per m^{-2}, respectively (Tracy and Sanderson 2000).

In the present study, the reduction in thistle density and biomass and damage to grasses caused by glyphosate, resulted in patches of bare-ground that were likely favorable for the germination and development of opportunistic, weedy, annual forb species from the soil seed bank. It is also possible that some seeds may have blown into the wiped plots from adjacent areas such as cultivated fields. In either case, the reduction in biomass of both thistle and grass likely led to increased soil temperatures, exposure to light, and access to moisture following precipitation, creating conditions favorable to the termination of seed dormancy (Roberts 1986; Begon et al. 1990).

As grass recovered in 2001, neither annual nor perennial forb biomass in wiped plots differed significantly ($P>0.05$) from untreated plots, although annual forb biomass remained visibly greater (i.e., by 734 $kg \cdot ha^{-1}$) within wiped plots ($P=0.06$; Table 5.5). Greater levels of annual forbs were particularly apparent on July wiped plots (Table 5.5). Precipitation in the spring and early summer of 2001 was lower compared to previous years at all sites, which may have limited forb growth in that year. It is also possible that treatment effects on herbage production had simply begun to diminish two years following the one-time glyphosate application, with the re-establishment of grasses leading to a gradual replacement of annual forbs in wiped plots.

5.3.2 Effects of Wiper-Applied Selective Herbicides

5.3.2.1 Canada Thistle Control

In 2000 and 2001, wiper-applied herbicide treatment resulted in significant ($P<0.01$) effects on all thistle variables (Table 5.6). In 2000, all herbicides had greater thistle mortality and lower live thistle shoot densities compared to untreated plots ($P<0.05$). Additionally, glyphosate resulted in significantly greater thistle mortality in 2000 than 2,4-D + mecoprop + dicamba, but did not differ from clopyralid or picloram + 2,4-D. In 2001, only clopyralid and picloram + 2,4-D maintained significantly ($P<0.05$) lower residual thistle shoot density and biomass than the check plots (Table 5.6). In 2002, herbicides resulted in overall non-significant ($P>0.10$) effects on thistle density and biomass, although trends similar to the year before were evident (Table 5.6). That is, clopyralid and picloram+2,4-D continued to have the lowest thistle density and biomass. Severe, widespread drought in 2002 may have contributed to the lack of differences (Table 5.3), or the effects of the one-time herbicide treatments may have begun to wane two years after application.

The results from 2000 are in agreement with Boerboom and Wyse (1988a), who found that in the year of treatment, ropewick-applied glyphosate, clopyralid, and picloram provided better Canada thistle control than dicamba in seed production fields of birdsfoot trefoil. The effectiveness of glyphosate, clopyralid, and picloram on Canada thistle control have been attributed to their rapid absorption and translocation throughout the thistle plant resulting in root kill (Sharma et al. 1971; Hunter and Smith 1972; O'Sullivan and Kossatz 1982, 1984; Turnbull and Stephenson 1985; Boerboom and Wyse 1988b).

For example, absorption and translocation studies have demonstrated reductions in root biomass and root bud numbers that, in turn, resulted in decreased secondary regrowth potential in Canada thistle following glyphosate (Carlson and Donald 1988), clopyralid (Donald 1988), and picloram (Hunter and Smith 1972). In contrast, dicamba has been shown in a number of studies to be better than 2,4-D, but generally less effective than glyphosate, clopyralid, or picloram, for controlling Canada thistle (e.g., Hunter and Smith 1972; Peterson and Parochetti 1978; Boerboom and Wyse 1988a). Hunter and Smith (1972) reported that spray applications of 2,4-D and dicamba, each at 1.12 $kg \cdot ha^{-1}$, and picloram at 0.14 and 0.28 $kg \cdot ha^{-1}$, all resulted in top growth control of Canada thistle, but only picloram severely damaged the root system. Both dicamba and 2,4-D resulted in leaf and shoot tissue damage, while dicamba caused more extensive damage than 2,4-D (Hunter and Smith 1972).

Several mechanisms have been postulated for these differences in herbicide efficacy. First, dicamba phytoxicity to Canada thistle may simply be inherently greater than 2,4-D but less than that of other herbicides such as glyphosate, clopyralid, and picloram. Second, while translocation of dicamba following foliar and root uptake has been documented in Canada thistle (Chang and Vanden Born 1968) and other weeds (Chang and Vanden Born 1971), dicamba does not accumulate in the roots to the same degree as either clopyralid (O'Sullivan and Kossatz 1984; Turnbull and Stephenson 1985) or picloram (Sharma et al. 1971). Instead, dicamba results in more rapid leaf and shoot tissue damage (e.g., xylem and phloem disruption) following application, which has been hypothesized to impair subsequent translocation to the roots (Chang and Vanden Born 1968; Hunter and Smith 1972). In contrast, Hunter and Smith (1972) found that

picloram caused less leaf tissue damage, but resulted in extensive swelling, splitting, and deterioration throughout the root system, which did not occur with either 2,4-D or dicamba. Widespread root damage was attributed to rapid translocation of picloram from the foliage, as leaves and shoots were only slightly injured after treatment and did not greatly inhibit picloram transport (Hunter and Smith 1972). This is consistent with Sharma et al. (1971), who documented rapid absorption and translocation throughout Canada thistle, including the roots.

In the present experiment, residual thistle control 1 and 2 years following treatment would have depended on the amount and extent of initial root kill (related to effectiveness of absorption and translocation), and the possible inhibition of subsequent thistle regrowth through soil residual effects. Clopyralid and picloram provided the greatest residual control of Canada thistle one year following treatment, while glyphosate and 2,4-D + mecoprop + dicamba exhibited non-significant thistle control one year after treatment (Table 5.6).

The observed longer-term effectiveness of picloram for Canada thistle control was likely due to its ability to enter and translocate through the plant very rapidly (Sharma et al. 1971), its ability to severely damage the root system (Hunter and Smith 1972; Peterson and Parochetti 1978), and its long persistence in the soil (Herr et al. 1966; Vanden Born 1969; Phillips and Feltner 1972; Alberta Agriculture, Food, and Rural Development 2003). Soil residual activity of picloram has been reported up to 5 years following treatment (e.g., Alberta Agriculture, Food, and Rural Development 2003), which may result in root system kill either directly, through the prolonged availability of

herbicide for absorption and translocation to the site of action, or indirectly, by preventing shoot regrowth and causing root starvation.

Effects of clopyralid on Canada thistle (e.g., patterns of absorption and translocation, including accumulation in roots) are similar to picloram, owing largely to their similarities in chemical structure (i.e., both are pyridinecarboxylic acid herbicides). Notable differences are that clopyralid controls thistle at much lower rates than picloram, and persistence is shorter, though soil residual activity of clopyralid has been reported up to one year after treatment (O'Sullivan and Kossatz 1984; Turnbull and Stephenson 1985; Alberta Agriculture, Food, and Rural Development 2003). In contrast, while absorption and translocation of glyphosate throughout thistle plants resulting in root-kill has been well-documented (e.g., Boerboom and Wyse 1988, Carlson and Donald 1988), glyphosate has virtually no soil persistence because of its very short half life (Alberta Agriculture, Food, and Rural Development 2003) and in general, is not as phytotoxic to Canada thistle as clopyralid, as much lower rates of clopyralid provide equally effective control (Donald 1990).

Greater initial root kill with picloram compared to glyphosate is consistent with the findings of Lauridson et al. (1983), who reported that picloram resulted in significantly shorter root lengths of Canada thistle compared to dicamba and glyphosate in both greenhouse and field studies. In addition, the removal of thistle and grass (growing intertwined with thistle plants at the time of treatment) by glyphosate visibly created micro-sites (i.e., bare-ground) that probably favored thistle re-establishment. This may have contributed to the lack of differences in both thistle density and biomass

between check and glyphosate plots compared to clopyralid and picloram+2,4-D the year following treatment.

The concentrations of glyphosate, 2,4-D + mecoprop + dicamba, and picloram + 2,4-D used in the present study were comparable to the rates used by Boerboom and Wyse (1988a). However, the concentration of clopyralid used here (i.e., 2%) was much lower than that of the fore-mentioned study (10 and 33%). Given the cost-equivalency of the treatments used here, it appears low concentrations of clopyralid and mid-range concentrations of picloram + 2,4-D may be the most appropriate for achieving longer-term control of Canada thistle in pastures with wiping. Boerboom and Wyse (1988b) found that lower concentrations of glyphosate (e.g., 2.5%) resulted in significantly greater thistle control than higher rates (e.g., 10 and 33%). Greater glyphosate concentrations were hypothesized to have resulted in more rapid tissue toxicity, which reduced translocation and thistle control (Boerboom and Wyse 1988b). It is possible that in the present experiment, increased translocation and better root-kill may have occurred, in turn leading to longer-term thistle control, with glyphosate concentrations less than the label recommendation of 33%, and merits further investigation.

5.3.2.2 Effects on Forage Production and Sward Components

Grass and forb (annual and perennial) biomass, as well as legume cover, were significantly affected by herbicide treatment in 2001 ($P \leq 0.05$). In 2002, effects on herbage production (Table 5.7), along with dandelion and legume cover (Table 5.8) were non-significant ($P > 0.05$). In 2001, grass biomass was lower in glyphosate-wiped plots ($P < 0.05$) compared to all other treatments. Glyphosate-wiped plots also had greater

annual forb biomass than check, clopyralid, and picloram+2,4-D plots in 2001 (Table 5.7).

The lower grass and greater annual forb biomass in glyphosate plots in 2001 parallels the results of the first experiment. Grass plants intertwined within thistle plants likely came in contact with glyphosate, resulting in grass kill and subsequent invasion by annual, weedy forbs. The lack of significant differences ($P>0.05$) in total herbage (grass+forb) production among treatments in 2002 (Table 5.7) was likely a result of very low growing season precipitation (Table 5.2), and the likelihood that grasses in glyphosate-wiped plots had begun to recover.

In 2001, glyphosate plots also resulted in the most perennial forb biomass (dandelion, white clover; Table 5.7), which was significantly greater ($P<0.05$) than the picloram + 2,4-D treatment, although it did not differ from the untreated check ($P>0.05$). Legume cover did not differ between untreated and glyphosate-wiped plots, but both were significantly ($P<0.05$) greater than the other three herbicide treatments (Table 5.7). The significant ($P<0.01$) block X treatment effect for legume cover in 2001 (Table 5.7) was primarily driven by treatment differences at the Edmonton site (data not shown), as differences were weak at the Morinville and Wetaskiwin sites for reasons that were unclear, but may have been related to lower than average precipitation in the spring and early summer of 2001 (Table 5.3). At the Edmonton site in 2002, legume cover remained lower in plots wiped with selective herbicides, although this difference was not significant (Table 5.8). Nevertheless, the legume trends in 2002 were similar to the previous year (i.e., glyphosate-wiped and check plots had more legume cover than all other herbicide-wiped plots, and legume cover was greatest in glyphosate plots, Table

5.8). Similarly, dandelion abundance did not differ among treatments at the Wetaskiwin site in 2002 (Table 5.8).

Perennial forbs sampled in 2001 consisted almost exclusively of dandelion and legumes such as alsike and white clover. The abundant legume cover in glyphosate-wiped plots was due largely to white clover, which was observed in high densities in 2001 and 2002. White clover is an important pasture legume in many temperate countries and is widespread across Canada (Turkington and Burdon 1983). However, it is also considered an agricultural escape and a minor weed in turf, lawns, and along roadsides because of its rapid colonization following soil disturbance. Turkington and Burdon (1983) noted that reproduction from seed was a common means of rapid colonization of white clover on disturbances such as molehills. The creation of bare-ground in glyphosate-wiped plots likely created conditions (i.e., release from grass and thistle competition, along with increased light and temperature) favorable not only for the germination and growth of annual, weedy forbs, but for white clover as well. Additionally, it appears glyphosate may not injure clover to the extent of 2,4-D + mecoprop + dicamba, clopyralid, and picloram + 2,4-D. Reasons for this are likely due to the short half life and lack of soil persistence of glyphosate compared to clopyralid and picloram, which can persist in soils for 1 and up to 5 years, respectively, after application.

Our results are consistent with those of Boerboom and Wyse (1988a), who found wiped glyphosate resulted in less injury to birdsfoot trefoil than dicamba, clopyralid, or picloram. These authors also found that wiper-applied picloram significantly reduced birdsfoot trefoil. In the present study, legumes (clover) were reduced by 2,4-D+mecoprop+dicamba, clopyralid, and picloram+2,4-D, 1 year after treatment (2001).

At the Edmonton site, though cover was still lowest in plots treated with picloram+2,4-D, differences in legume cover among treatments by 2002 were not significant, suggesting clover had begun to recover or re-establish (Table 5.8).

Broadcast spray applications of dicamba, clopyralid, and picloram have been shown to control Canada thistle, with clopyralid and picloram providing longer-term control (Amor and Harris 1977; Reece and Wilson 1983; Donald 1990). However, in pastures dominated by white clover and perennial ryegrass (*Lolium perenne* L.) in Australia, Amor and Harris (1977), found picloram + 2,4-D eliminated white clover for at least two years following treatment. In contrast, our results indicate that while wiping with picloram + 2,4-D at 20% concentration may decrease white clover 1 year later, within 2 years, clover may exhibit significant recovery to levels similar to untreated areas.

5.4 Conclusions and Management Recommendations

This research indicates weed-wipers are a suitable alternative to broadcast spraying for perennial weed control in permanent pastures. Advantages of wiping compared to spraying include environmental benefits, such as decreased herbicide drift and damage to non-target species, as well as economic benefits, such as reduced damage to legumes and lower cost, as the amount of herbicide used is proportional to the amount of weeds treated. We attempted to determine whether weed wiping with glyphosate, 2,4-D + mecoprop + dicamba, clopyralid, and picloram+2,4-D were feasible for Canada thistle control in pastures.

In terms of management recommendations, glyphosate at 33% of the commercial formulation, sponge wiper-applied at either the late bud or fluff stage, may provide control of Canada thistle for up to two years following application. Because of the non-selective nature of glyphosate, adequate height separation between target thistle plants and the associated forage stand appears critical. Even with heavy grazing to achieve height separation, sponge wiper-applied glyphosate impaired grass growth for up to a year following treatment, which in turn, led to the invasion of weedy annuals. Although glyphosate may not affect lower-statured legumes, the benefits from suppression of Canada thistle and maintenance of legumes may not out-weigh the reduction in grass production and subsequent increase in annual weeds. Therefore, wiping with glyphosate for Canada thistle control in pastures under label recommendations is questionable.

Among selective herbicides, sponge wiper-application of 2,4-D + mecoprop + dicamba at 24% commercial concentration did not significantly reduce Canada thistle one year following treatment. In contrast, suppression of Canada thistle was achieved for two years following a one-time application with both clopyralid and picloram + 2,4-D, at v/v concentrations of 2% and 20% (7 g a.i. L^{-1}, and 13 + 48 g a.i. L^{-1}respectively). Although 2,4-D + mecoprop + dicamba, clopyralid and picloram + 2,4-D did not eliminate legume cover, they did significantly reduce this component 1-year after application. Wiped clopyralid, picloram + 2,4-D, and 2,4-D+mecoprop+dicamba had the added benefit of maintaining grass production and minimizing weed invasion, which suggests that these herbicides may provide a viable alternative to broadcast spraying or wiping with glyphosate for Canada thistle control in pastures, particularly those containing little

legume. Differences in longer-term efficacy among the four herbicides tested were likely due to differences in herbicide uptake and translocation to roots, and soil residual effects.

5.5 Literature Cited

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Table 5.1 Location, soils, and vegetation characteristics for Experiment 1 (glyphosate-wiper) and Experiment 2 (multiple herbicides-wiper) pasture sites as sampled in August and September of 1999, and August of 2000, respectively.

Location	Lat. / Lon.	Landform[z]	Texture / Soil type	Dominant vegetation		Initial thistle density (no.m^{-2})[x]
				Grass species	Forb species[y]	
1. Glyphosate Experiment						
Barrhead	54° 00' 57" N 114° 22' 44" W	Floodplain	Silt Loam, Orthic Humic Gleysol	Quackgrass (*Agropyron repens* (L.) Beauvois), Kentucky bluegrass (*Poa pratensis* L.), Meadow bromegrass (*Bromus biebersteinii* Roem. & Schult.)	Dandelion, (*Taraxacum officinale* Web.)	72
Lamont	53° 42' 24" N 112° 33' 10" W	Level moraine	Silty Clay Loam, Orthic Black Chernozem	Smooth brome (*Bromus inermis* Leyss.), Kentucky bluegrass	Dandelion, Common yarrow (*Achillea millefolium* L.)	31
Spruce Grove	53° 33' 31" N 113° 49' 48" W	Level moraine	Loam, Orthic Black Chernozem	Canada bluegrass (*Poa compressa* L.), Smooth brome, Quackgrass	Dandelion, Alsike clover, (*Trifolium hybridum* L.)	24
Thorsby	53° 12' 37" N 114° 15' 48" W	Level moraine	Loam, Orthic Black Chernozem	Kentucky bluegrass, Timothy (*Phleum pratense* L.)	Dandelion, White clover (*Trifolium repens* L.)	35
2. Multiple Herbicides Experiment						
Edmonton	53° 30' 08"N 113° 33' 44"W	Floodplain	Silty Clay Loam, Orthic Black Chernozem	Kentucky bluegrass, quackgrass, smooth brome	White clover, dandelion	29
Morinville	53° 46' 46" N 113° 43' 51" W	Level moraine	Silty Clay Loam, Orthic Black Chernozem	Kentucky bluegrass, quackgrass, smooth brome, timothy	White clover, dandelion	12
Wetaskiwin	52° 58' 33" N 113° 39' 51" W	Level moraine	Silt Loam, Orthic Black Chernozem	Kentucky bluegrass, quackgrass, smooth brome, timothy	Alsike and white clover, dandelion	36

[z]The slope at all sites was ≤ 2%.
[y]Initial clover cover in the untreated check plots in 2000 for Experiment 2 at Edmonton, Morinville, and Wetaskiwin were 14%, 10%, and 36%, respectively.
[x]Number of Canada thistle shoots m^{-2} in the untreated check plots in 1999 for Experiment 1, and in 2000 for Experiment 2.

Table 5.2 Soil characteristics for the three pastures sites of the multiple herbicides experiment, as sampled in August of 2001[z].

Location	pH	E.C. (dS/cm)	O.M. (%)	Nutrients ($kg\,ha^{-1}$)			
				N	P	K	S
Edmonton	6.6	0.33	11.9	< 6	160	1883	27
Morinville	7.1	0.41	9.3	7	22	585	74
Wetaskiwin	7.3	0.62	14.6	< 4	25	395	17

[z]All values represent the average of the two soil depths that were sampled and analyzed separately (0-15 and 15-30 cm). Nitrogen, phosphorus, and sulfur were present in the form of nitrate, phosphate, and sulfate, respectively.

Table 5.3 Precipitation data for the four sites of the glyphosate wiper experiment (1999 – 2001), and the three sites of the multiple herbicides experiment (2000 – 2002).

Sites	May-August Precipitation (mm)				
	1999	2000	2001	2002	30-yr average
1. Glyphosate Experiment					
Barrhead	281	301	292	n/a	319
Lamont	235	272	279	n/a	263
Spruce Grove and Thorsby	297	304	310	n/a	318
2. Multiple Herbicides Experiment					
Edmonton and Morinville	n/a	269	299	129	313
Wetaskiwin	n/a	308	299	130	325

Table 5.4 Means and pooled SEs[z], as well as ANOVA *F* test significance values for Canada thistle variables, by timing of application, wiper treatment, and timing X wiper treatment combinations from 4 pasture sites in central Alberta for 1999 to 2001 (glyphosate experiment).

Source	df	1999		2000		2001[y]	
		Thistle mortality (%)	Thistle Density ($no\,m^{-2}$)	Thistle Density ($no\,m^{-2}$)	Thistle Biomass ($kg\,ha^{-1}$)	Thistle Density ($no\,m^{-2}$)	Thistle biomass ($kg\,ha^{-1}$)
1. Glyphosate Experiment							
Timing (T); n=16	1	F=1.63	F=0.50	F=0.44	F=1.45	F=0.09	F=0.05
		P=0.33	P=0.55	P=0.58	P=0.35	P=0.81	P=0.86
July		47	29	20	655	9	91
August		37	20	16	325	8	106
SE		5	9	4	193	1	48
Site (Timing) – error 1	2						
Wiper treatment (W); n=16	1	F=395.27	F=64.24	F=38.76	F=17.95	F=12.76	F=2.91
		P<0.001	P<0.001	P<0.001	P<0.001	P<0.01	P=0.11
Check		6	41	28	794	14	136
Wiped		78	8	9	187	4	55
SE		3	3	2	101	2	38
T X W; n=8	1	F=6.80	F=9.80	F=3.74	F=5.03	F=0.00	F=0.66
		P=0.02	P<0.01	P=0.07	P=0.03	P=0.95	P=0.43
July – check		7c	52a	33	1120a	14	117
wiped		87a	6c	7	191b	4	65
August – check		6c	30b	23	468b	13	176
wiped		68b	10c	10	182b	3	36
SE		4	4	3	143	3	54
W X Site (timing); n=4	2	F=2.13	F=4.07	F=3.81	F=8.30	F=0.48	F=0.46
		P=0.14	P=0.03	P=0.04	P<0.01	P=0.50	P=0.50
July[x]							
Barrhead – check		2	72a	43a	1785a	16	56
wiped		84	10b	6b	31b	4	47
Lamont – check		11	31a	22a	454b	12	177
wiped		90	2b	9b	351b	4	83
August							
Spruce Grove – check		8	24a	27a	554b	n/a	n/a
wiped		80	6b	11b	306b	n/a	n/a
Thorsby – check		5	35a	20a	382b	13	176
wiped		57	14b	8a	59b	3	36
SE		5	6	4	203	3	63
Residual error	24						

[z]Means and pooled SEs are calculated for untransformed data. *F* statistics, *P* values, and mean comparisons are based on untransformed data. Where applicable, Tukey's test (P<0.05) was used for intra-treatment comparisons. Means with different letters differ significantly at P<0.05. [y]The Spruce Grove site was lost in 2001. Therefore, in 2001, n=12 for timing and wiping treatment; n=4 for August timing X wiping interaction, and n=2 for wiper X site (timing). [x]Mean comparisons, where applicable, are within a site.

Table 5.5 Means and pooled SEs[z], as well as ANOVA *F* test significance values for annual net primary production variables, by timing of application, wiper treatment, and timing X wiper treatment combinations, from 4 pasture sites in central Alberta for 1999 to 2001 (glyphosate experiment).

Source	df	2000		2001[x]		
		Grass biomass ($kg \cdot ha^{-1}$)	Total forb biomass ($kg \cdot ha^{-1}$)[y]	Grass biomass ($kg \cdot ha^{-1}$)	Annual forb biomass ($kg \cdot ha^{-1}$)[y]	Perennial forb biomass ($kg \cdot ha^{-1}$)[y]
1. Glyphosate Experiment						
Timing (T); n=16	1	$F = 0.20$	$F = 0.02$	$F = 2.36$	$F = 0.09$	$F = 0.06$
		$P = 0.70$	$P = 0.91$	$P = 0.37$	$P = 0.82$	$P = 0.85$
July		2828	1143	2893	684	62
August		2176	694	875	273	67
SE		1025	484	915	15	54
Site (timing) – error 1	2					
Wiper treatment (W); n=16	1	$F = 7.13$	$F = 12.05$	$F = 0.31$	$F = 4.05$	$F = 0.00$
		$P = 0.01$	$P < 0.01$	$P = 0.58$	$P = 0.06$	$P = 0.96$
Check		2874	318	2376	180	59
Wiped		2131	1519	2065	914	70
SE		197	295	398	269	12
T X W; n=8	1	$F = 0.71$	$F = 2.92$	$F = 0.01$	$F = 1.37$	$F = 0.74$
		$P = 0.41$	$P = 0.10$	$P = 0.94$	$P = 0.26$	$P = 0.40$
July – check		3317	218	3062	165	66
wiped		2339	2068	2724	1203	59
August – check		2430	418	1003	210	52
wiped		1923	969	746	336	81
SE		278	417	556	311	14
W X site (timing); n=4	2	$F = 1.95$	$F = 0.52$	$F = 0.13$	$F = 0.23$	$F = 0.86$
		$P = 0.17$	$P = 0.60$	$P = 0.73$	$P = 0.64$	$P = 0.37$
July						
Barrhead – check		2214	396	2189	284	116
wiped		1086	2000	2081	1055	117
Lamont – check		4419	40	3936	45	17
wiped		3592	1328	3367	1352	0
August						
Spruce Grove–check		2896	134	n/a	n/a	n/a
wiped		3149	236	n/a	n/a	n/a
Thorsby – check		1965	702	1003	210	52
wiped		696	1702	746	336	71
SE		394	590	651	440	20
Residual error	24					

[z]Means and pooled SEs are calculated for untransformed data. Where applicable, Tukey's test ($P < 0.05$) was used for intra-treatment comparisons. Means with different letters differ significantly at $P<0.05$. [y]*F* statistics, *P* values, and mean comparisons of forb biomass data (annual and perennial) are based on square root transformed data. [x]The Spruce Grove site was lost in 2001. Therefore, in 2001, n=12 for timing and wiping treatment; n=4 for August timing X wiping interaction, and n=2 for wiper X site (timing).

Table 5.6 Means and pooled SEs[z], as well as ANOVA *F* test significance values for Canada thistle variables, by wiper herbicide treatment, from 3 pasture sites in central Alberta for 2000 to 2002 (multiple herbicides experiment).

Source of variation	df	2000		2001		2002[x]	
		Thistle mortality (%)	Thistle density ($no\,m^{-2}$)[y]	Thistle density ($no\,m^{-2}$)[y]	Thistle biomass ($kg\,ha^{-1}$)[y]	Thistle density ($no\,m^{-2}$)[y]	Thistle biomass ($kg\,ha^{-1}$)[y]
2. Multiple Herbicides Experiment							
Block	2	*F*=75.64	*F*=65.38	*F*=5.43	*F*=17.67	*F*=23.83	*F*=15.26
		P<0.001	*P*<0.001	*P*<0.01	*P*<0.001	*P*<0.001	*P*<0.001
Treatment (n=12)	4	*F*=38.82	*F*=16.59	*F*=3.98	*F*=4.04	*F*=1.69	*F*=1.40
		P<0.001	*P*<0.001	*P*<0.01	*P*<0.01	*P*=0.18	*P*=0.26
Check		30c	26a	29a	785a	32	606
Glyphosate		83a	4b	13ab	294ab	20	474
2,4-D+mecoprop+dicamba		67b	9b	12ab	370ab	20	187
Clopyralid		72ab	9b	8b	130b	14	134
Picloram + 2,4-D		74ab	8b	8b	81b	12	159
SE		3	2	3	216	4	153
Block X Treatment	8	*F*=1.63	*F*=0.76	*F*=0.22	*F*=0.22	*F*=0.06	*F*=0.59
		P=0.14	*P*=0.64	*P*=0.99	*P*=0.99	*P*=0.99	*P*=0.67
Residual Error	45						

[z]Means and pooled SEs are calculated for untransformed data. Where applicable, Tukey's test ($P < 0.05$) was used for intra-treatment comparisons. Means with different letters differ significantly at $P<0.05$. [y]*F* statistics, *P* values, and mean comparisons of thistle density and biomass are based on log(Y+1) transformed data. [x]The Morinville site was lost in 2002. Therefore, in 2002, n=8 for treatment.

Table 5.7 Means and pooled SEs[z], as well as ANOVA *F* test significance values for annual net primary productivity variables by wiper herbicide treatment, from 3 pasture sites in central Alberta for 2001 and 2002 (multiple herbicides experiment).

Source of variation	df	2001				2002[y]
		Grass biomass ($kg \cdot ha^{-1}$)	Annual forb biomass ($kg \cdot ha^{-1}$)	Perennial forb biomass ($kg \cdot ha^{-1}$)	Legume cover (%)	Total herbage biomass ($kg \cdot ha^{-1}$)
2. Multiple Herbicides Experiment						
Block	2	F=7.45	F=0.66	F=0.83	F=31.75	F=5.47
		P<0.01	P=0.52	P=0.44	P<0.001	P=0.03
Treatment (n=12)	4	F=2.47	F=3.48	F=2.92	F=5.81	F=0.42
		P=0.05	P=0.02	P=0.03	P<0.001	P=0.79
Check		2994a	38b	142ab	13a	2250
Glyphosate		1818b	1797a	359a	17a	2118
2,4-D+mecoprop+dicamba		3144a	332ab	188ab	6b	2120
Clopyralid		3351a	1b	178ab	5b	2075
Picloram + 2,4-D		3409a	22b	45b	3b	2315
SE		414	413	67	3	158
Block X Treatment	8	F=0.70	F=0.71	F=1.17	F=3.41	F=0.68
		P=0.69	P=0.68	P=0.34	P<0.01	P=0.61
Residual Error	45					

[z]Means and pooled SEs are calculated for untransformed data. Where applicable, Tukey's test ($P < 0.05$) was used for intra-treatment comparisons. Means with different letters differ significantly at P<0.05. [y]The Morinville site was lost in 2002. Therefore, in 2002, n=8 for treatment.

Table 5.8 Means and pooled SEs, as well as ANOVA *F* test significance values for legume and dandelion cover by wiper herbicide treatment at two pasture sites in central Alberta for 2002.

Source of variation	df	2002	2002
		Legume cover (%; Edmonton site)[z]	Dandelion cover (%; Wetaskiwin site)[y]
2. Multiple Herbicides Experiment			
Rep	3	F = 6.45	F = 4.71
		P < 0.01	P = 0.02
Treatment (=8)	4	F = 0.64	F = 1.34
		P = 0.64	P = 0.31
Check		25	5
Glyphosate		27	15
2,4-D+mecoprop+dicamba		13	21
Clopyralid		19	14
Picloram+2,4-D		11	5
SE		9	6
Residual error	19		

[z]Legume cover is from the Edmonton pasture site only.
[y]Dandelion cover is from the Wetaskiwin pasture site only.

6. SYNTHESIS / CONCLUSION

Canada thistle is an aggressive, perennial weed that invades pastures and hay land throughout western Canada (Moore 1975). Its noxious character is attributable to its capacity for rapid, vegetative spread due to its extensive, creeping root system, and it's adaptability to a wide range of ecological niches. The purpose of this research was to quantify forage losses due to Canada thistle, explore the integrated use of herbicides and fertilizer for controlling Canada thistle, and assess the utility of a sponge wiper for controlling Canada thistle in Alberta pastures. Several field experiments were established to address these objectives. Our results represent an initial attempt at addressing some of the key issues behind the Canada thistle problem in pastures under western Canadian growing conditions.

The first study, a series of yield loss assessments monitored over 3 years, indicated that Canada thistle often reduced forage biomass, but that this response varied among different pastures, with some sites having significant yield loss relationships, while others did not (Chapter 3). Inconsistent responses among locations were likely related to site differences, such as initial thistle density and biomass, local growing conditions and moisture regime, species composition, rodent disturbances, and soil type or nutrient status.

Pasture conditions are inherently more variable than cultivated, annual crop land, where the majority of yield loss assessments due to Canada thistle have been conducted up to this point (e.g., O'Sullivan et al. 1982; 1985). As a result, pasture yield loss

assessments appear to be more difficult to obtain than those in annual crops. Moreover, management recommendations for assessing pasture yield loss due to Canada thistle must be made based on site-specific conditions. Despite these logistical challenges encountered in the yield loss assessment study, Canada thistle was found to reduce forage biomass at more than one site, highlighting the potential negative impacts on pasture forage yields and confirming the need for livestock producers to actively manage this weed. Our findings therefore represent a launching point for future investigations on the mechanisms behind thistle yield impacts on forage stands (e.g., competition, allelopathy). For example, the importance of underground, root-to-root competition effects in the context of permanent pastures requires better understanding. Additionally, the importance of ecological factors in influencing Canada thistle impacts on forage yield, such as initial thistle abundance, forage vigor and species composition, soils, and precipitation, also warrants further investigation.

The second experiment compared the integrated effects of one-time mowing or herbicide application, with and without annual spring fertilization, on Canada thistle abundance and forage response, over a 3-year period (Chapter 4). Our results found that one-time mowing did not provide adequate control of Canada thistle, and that when combined with fertilization, actually increased Canada thistle abundance. Fertilization enhanced Canada thistle control with herbicides for several years after spraying, likely due to increased competition from the grass stand. All herbicides significantly reduced Canada thistle abundance in 1999, but clopyralid and picloram+2,4-D provided longer-term control.

While specific recommendations for thistle control will vary depending on forage sward composition and management objectives, our results underscore the benefits of combining more than one management tool (e.g., herbicides and fertilizer) into an integrated strategy. Ultimately, the choice of herbicide will be determined by economic considerations, efficacy, and residual / re-cropping concerns. Canada thistle-infested pastures containing a large proportion of desirable legumes may be more difficult to manage if maintaining legumes is a high priority, as all herbicides reduced legumes; an effect exacerbated when combined with fertilization.

Our results also underscore the importance of fertilization in enhancing longer-term suppression of Canada thistle with herbicides. Moreover, without an associated thistle control measure, fertilization alone may make an already existing thistle problem worse. This information could prove useful for ranchers and land managers, as knowledge that fertilization alone may not be a benefit in thistle-infested pastures and rangeland may encourage the integration of complementary control strategies into more appropriate management programs. Future research on the mechanisms of herbicide efficacy (e.g., absorption, uptake, translocation, and soil residual effects) in a permanent pasture setting would build on the present experiment, as would greenhouse and field investigations of the biological and ecological mechanisms behind the enhancement of Canada thistle control with fertilization (e.g., root and shoot competition for water, light, and nutrients). In addition, cost-benefit analyses of thistle control using integrated strategies, such as herbicides and fertilizer, are needed, as this information could aid producers in the decision-making process associated with Canada thistle management in pastures.

The last pair of experiments conducted in this research investigated the utility of a sponge weed wiper for controlling Canada thistle in pastures. Wiper-applicators are an alternative to broadcast spraying, and our results supported the general utility of this technology as a possible option for integration into a weed management strategy. Advantages of wiping compared to spraying may include economic benefits, such as lower cost, because the amount of herbicide used is proportional to the amount of weeds treated, and environmental benefits, such as decreased herbicide drift and damage to non-target species.

Our results suggest that while wiper-applied glyphosate may suppress Canada thistle and retain legumes, the potential decrease in grass production and subsequent increase in annual weeds may not justify its use. In contrast, wiper-applied clopyralid and picloram+2,4-D provided thistle suppression for up to two years following a one-time treatment, and while legumes were reduced by all selective broad-leaf herbicides tested, grass production was maintained compared to glyphosate.

Overall, this research indicates that wiper-applied selective herbicides are a feasible alternative to broadcast spraying or wiping with glyphosate for Canada thistle control in pastures. Future research on Canada thistle control in pastures using wipers might consider comparisons of both the efficacy and economics of spraying versus wiping, including estimates of the quantity of herbicide wiped onto thistle plants. Additionally, cost-benefit analyses that take into account both the cost associated with the removal of desirable legumes, as well as the benefits of increased grass production from thistle suppression with herbicides, are needed.

Canada thistle is a noxious weed, which gives local and provincial jurisdictions the authority to enforce its control (Government of Alberta 2001). Additionally, results from yield loss assessments in the present study indicated that Canada thistle reduced forage biomass at a number of different locations. Therefore, a strong rationale exists for Canada thistle control in pastures, along with a need by ranchers, land managers, and extension personnel, for management information. Both broadcast spray and wiper-applied herbicides provide Canada thistle suppression in pastures, and are useful options for dealing with this weed problem. Furthermore, our findings suggest that integrated management strategies, such as herbicides and fertilizer applied in combination, may provide better control than thistle control measures applied individually, and represent a practical approach to dealing with the Canada thistle problem in pastures.

6.1 Literature Cited

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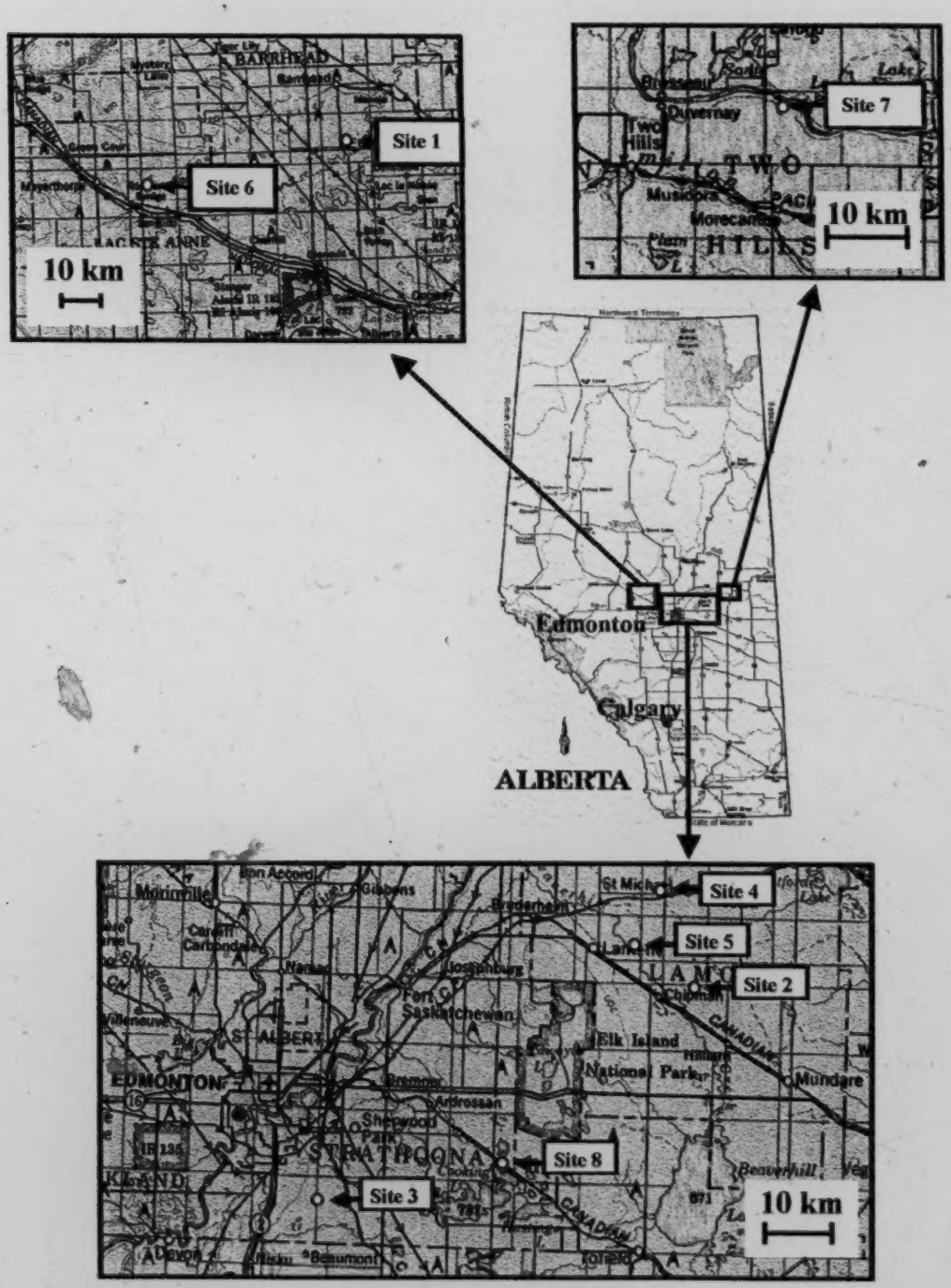
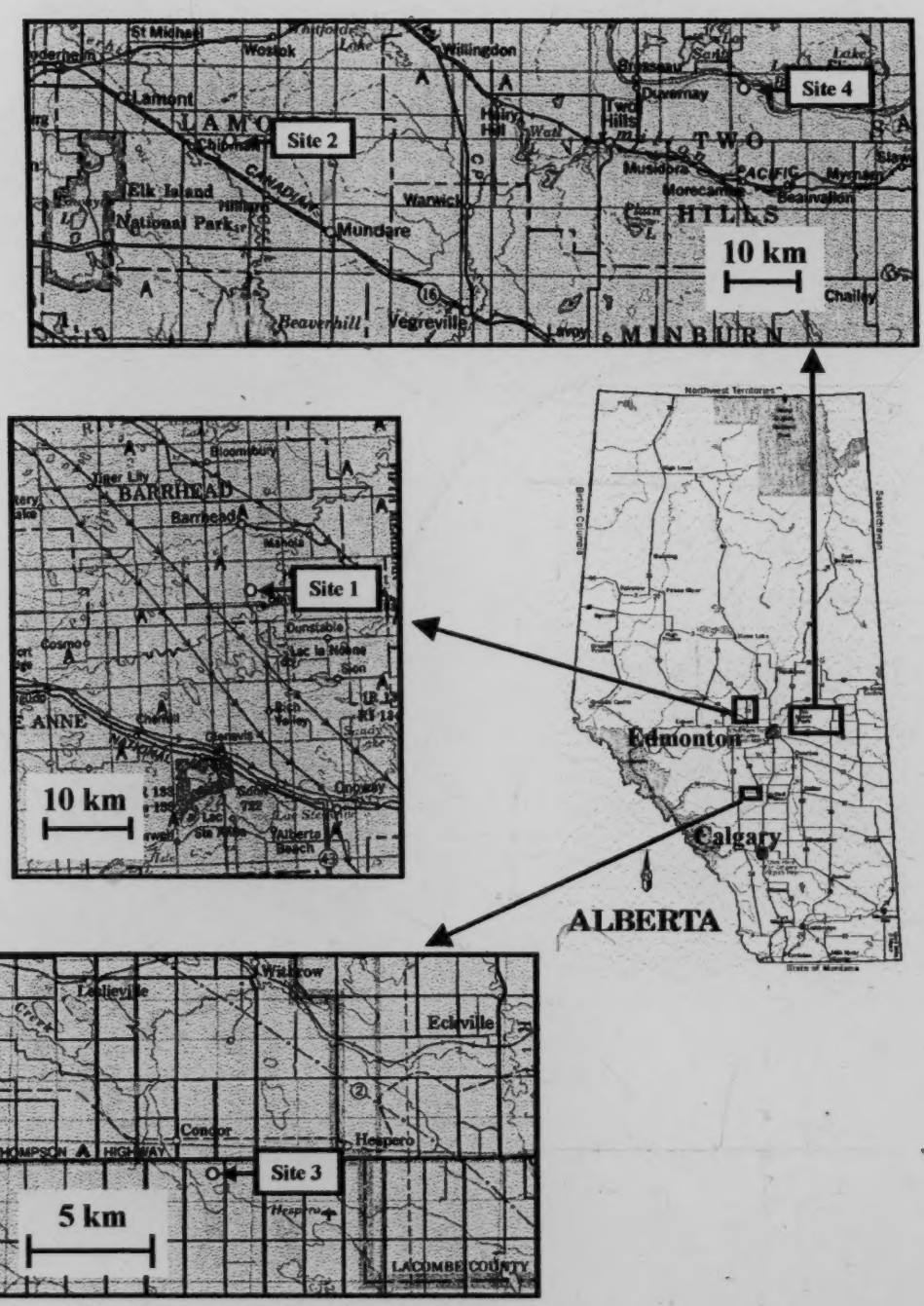
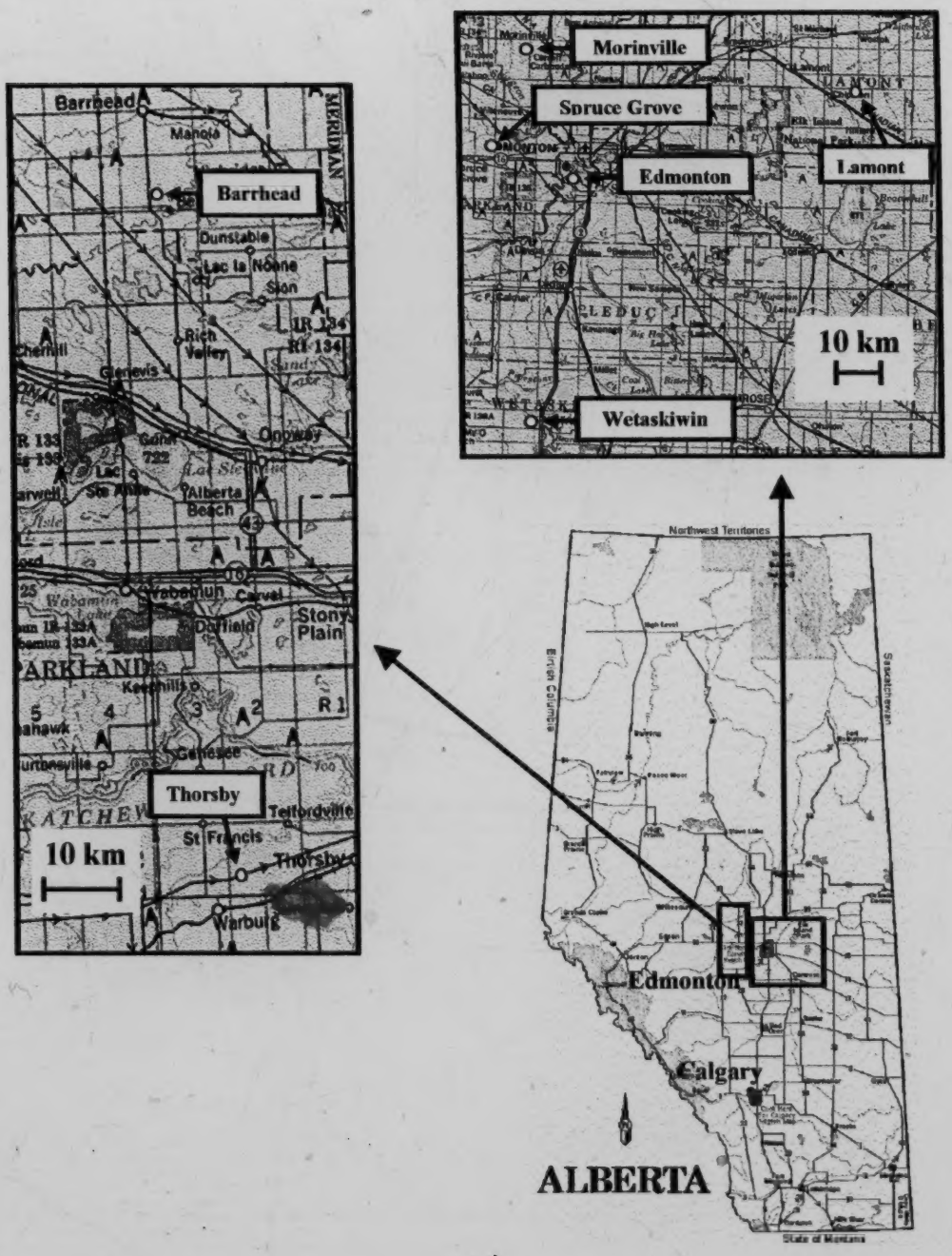
Appendix 1: Maps of the study locations.



Appendix 1.1: Locations of the 8 pasture yield loss assessment sites (Chapter 3).



Appendix 1.2: Locations of the 4 pasture sites of the efficacy study (Chapter 4).



Appendix 1.3: Locations of the 7 pasture sites of the wiper study (Chapter 5).

Appendix 2: Soil descriptions.

Appendix 2.1 Soil description for Site 1 (Barrhead; Chapter 4).

Pedon description – Orthic Humic Gleysol

Horizon	Depth (cm)	Description
Oh	-21 - 0	Dark reddish brown (2.5YR3/4 d); semi-decomposed organic matter; plentiful, fine, random, exped roots; abrupt, wavy boundary; 15 to 25 cm thick.
Ah	0-24	Black (10YR2/1 m); silty clay loam; few, fine, distinct, reddish brown (2.5YR 4/8) mottles; moderate medium granular; friable; plentiful, fine, random, inped roots; abrupt, wavy boundary; 20-30 cm thick.
Bg	24-79	Light brownish gray (10YR6/1 m); silty clay; many, coarse, prominent, brown (10YR4/6) mottles; strong, medium, subangular blocky; firm; few, fine, random, inped roots; abrupt, wavy boundary; 50-60 cm thick.
Cg	79+	Light brownish gray (10YR6/2 m); clay; moderate medium angular blocky; slightly hard.

Site Description

Landform	Floodplain.
Slope	Level.
Aspect	N/A
Dominant Plant Species	Quackgrass (*Agropyron repens* (L.) Beauvois), Kentucky bluegrass (*Poa pratensis* L.), Meadow bromegrass (*Bromus biebersteinii* Roem. & Schult.)
Drainage Class	Imperfectly drained.

Appendix 2.2 Soil description for Site 2 (Lamont; Chapter 4).

Pedon description – Orthic Black Chernozem

Horizon	Depth (cm)	Description
Ah	0-34	Black (10YR2/1 d); silty loam; weak, fine, granular; slightly hard; plentiful, fine, random, exped roots; abrupt, wavy boundary; 30-44 cm thick.
AB	34-47	Brownish black (10YR2/3 d); silty clay loam; weak, fine, granular; slightly hard; plentiful, fine, random, inped roots; abrupt, wavy boundary; 10-15 cm thick.
Bm	47-94	Brown (10YR4/4 m); silty clay; moderate, medium, angular blocky; hard; few, fine, random, inped roots; abrupt, smooth boundary; 40-50 cm thick.
Cca	94+	Dull yellowish brown (10YR5/3 m); clay loam; moderate, medium, angular blocky; slightly hard.

Site Description

Landform	Moraine
Slope	Level
Aspect	N/A
Dominant Plant Species	Smooth brome (*Bromus inermis* Leyss.), Kentucky bluegrass (*Poa pratensis* L.)
Drainage Class	Well-drained.

Appendix 2.3 Soil pedon description for Site 3 (Rocky Mountain House; Chapter 4).

Pedon description – Orthic Black Chernozem

Horizon	Depth (cm)	Description
Ah	0-25	Black (10YR2/1 d); silty loam; moderate, medium, granular; hard; plentiful, fine, random, inped roots; abrupt, wavy boundary; 21-28 cm thick.
Bm1	25-51	Dull yellowish brown (10YR5/4 d); clay loam; moderate, medium, subangular blocky; hard; few, fine, random, inped roots; abrupt, wavy boundary; 20-30 cm thick.
Bm2	51-81	Yellowish brown (10YR5/8 m); sandy clay loam; weak, fine, granular; soft; abrupt, wavy boundary; 25-35 cm thick.
Cca	81+	Yellowish brown (10YR5/4 m); clay; moderate, medium, angular blocky; hard.

Site Description

Landform	Rolling moraine
Slope	< 2%
Aspect	South
Dominant Plant Species	Quackgrass (*Agropyron repens* (L.) Beauvois), Kentucky bluegrass (*Poa pratensis* L.)
Drainage Class	Well-drained.

Appendix 2.4 Soil pedon description for Site 4 (Two Hills; Chapter 4).

Pedon description – Gleyed Dark Gray Chernozem

Horizon	Depth (cm)	Description
Ahe	0-20	Dark brown (10YR3/3 d); silty loam; weak, fine, granular; soft; plentiful, fine, random, exped roots; clear, wavy boundary; 10-25 cm thick.
Bmgj1	20-47	Brown (10YR4/4 m); silty clay loam; common, medium, distinct, reddish brown (5YR 4/6) mottles; moderate, medium, subangular blocky; friable; few, fine, random, inped roots; gradual, wavy boundary; 25-30 cm thick.
Bmgj2	47-70	Brown (7.5YR5/8 m); clay loam; many, coarse, prominent, reddish brown (5YR 4/6 m) mottles; moderate, medium, subangular blocky; friable; very few, very fine, vertical, inped roots; abrupt, smooth boundary; 20-25 cm thick.
Cca	70+	Brownish gray (10YR6/1 m); clay loam; moderate, medium, subangular blocky; friable.

Site Description

Landform	Hummocky moraine
Slope	< 4%
Aspect	West
Dominant Plant Species	Smooth brome (*Bromus inermis* Leyss.), Kentucky bluegrass (*Poa pratensis* L.)
Drainage Class	Moderately well-drained.